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DEVELOPMENT OF A NICAD BATTERY INTERFACE UNIT.(U)
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DEVELOPMENT OF A NICAD BATTERY INTERFACE UNIT

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December 1978

Final Report for Period July 1976 - May 1978

Approved for public release;
distribution unlimited.

Prepared for

APPLIED TECHNOLOGY LABORATORY
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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This Laboratory concurs in the findings of this report and recommends the use of this type of equipment on Army aircraft. Several manufacturers have recently introduced chargers that are similar to the units described herein. It is recommended that each unit be judged on its own merits.

The technical monitor for this program was Mr. Joseph D. Dickinson of the Applied Aeronautics Technical Area, Aeronautical Systems Division.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 18 USARTL 19 TR-78-47	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 DEVELOPMENT OF A NICAD BATTERY INTERFACE UNIT.		5. TYPE OF REPORT & PERIOD COVERED 9 FINAL REPORT. July 1976-May 1978 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 EARNEST STEPHENS		8. CONTRACT OR GRANT NUMBER(s) 15 DAAJ02-76-C-0054
9. PERFORMING ORGANIZATION NAME AND ADDRESS CHRYSLER CORPORATION MICHOUD DEFENSE-SPACE DIVISION P.O. BOX 29200, NEW ORLEANS, LA 70189		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62209A 1F262209AH76 00 159EK 16 17 DD
11. CONTROLLING OFFICE NAME AND ADDRESS APPLIED TECHNOLOGY LABORATORY U.S.ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM), FORT EUSTIS, VA 23604		12. REPORT DATE 11 December 1978 13. NUMBER OF PAGES 74
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 75 p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aircraft Battery Charger, Nickel-Cadmium Battery, Onboard Equipment, Battery Status Monitoring		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the effort to develop and test a Battery Interface Unit (BIU) for use on Army aircraft. The BIU provides a means to charge and monitor the status of nickel-cadmium batteries and is an onboard unit that can be readily integrated with the existing aircraft electrical system. The initial portion of the multitask program involved definition of candidate approaches, analysis to select the optimum approach, and design of a system to implement the multilevel, constant current approach selected as optimum. Six BIU's were then fabricated, three to operate with an AC input and three		

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to operate from a DC input; they were subjected to a variety of performance and environmental tests to demonstrate performance. The objectives of the program were to develop a system that would reduce battery maintenance cost, increase the useful life of NICAD batteries, and eliminate battery-related safety hazards. The results of the program clearly demonstrated that a BIU can be built which meets these objectives and which can be packaged within weight and volume limits compatible with onboard aircraft usage.

SUMMARY

The nickel-cadmium battery has been used on Army aircraft for a number of years. This type of battery has not, however, fulfilled its full potential in terms of reliability, maintainability, and safety, due in large measure to improper charging and monitoring of the battery. Though it has been recognized that an onboard battery charger/monitor would alleviate or eliminate most of the problems with NICADS, the type of charge technique best suited to the application and the quantitative benefits of such a system had not been clearly defined. This report describes the effort to develop and test a Battery Interface Unit (BIU) which would establish a baseline for present and future aircraft systems.

The objective of the program was to develop a Battery Interface Unit that eliminated present problems with inadequate battery life, excessive battery maintenance, thermal runaway and insufficient battery status information. As detailed in the report, the BIU's developed during the program do meet these objectives. Further, the resulting units are compatible with weight and volume requirements for aircraft equipment.

The program was evolutionary in nature. In the initial portion of the program (Task I), the general requirements for the BIU were established and eight different concepts for an onboard charger were defined. Based on the results of this effort, a detailed comparative evaluation of each concept was made (Task II). The results of this effort showed that while any of the onboard chargers was superior to the constant-potential method of charging aircraft batteries, the multilevel constant current charger was the preferred approach.

Task III involved the design and Task IV the fabrication of three BIUs to implement the approach selected in Task II. These units operated with an AC input. After the program was underway, three additional BIU's (Task VI) were added. These units, operated from a DC input, were similar to the AC input units with the exception of the input power circuits.

The six BIUs were subjected to a variety of tests during Task V. Environmental tests demonstrated that the units can withstand stresses imposed by aircraft usage. Though electromagnetic interference (EMI) could be a problem, the EMI tests indicated that proper filtering can eliminate this problem without unacceptable performance penalties. The performance tests clearly demonstrated the advantages of a BIU in comparison with constant potential charging. Proper selection of the current level used for the third step in the three-step charge technique can lead to a balance between water loss and capacity loss which, in application, could result in a significant reduction in scheduled battery maintenance. Life-cycle tests demonstrated that the BIUs greatly reduce unscheduled battery maintenance. In over 3,000 cycles, no failures in either the battery or BIU were experienced.

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INTRODUCTION

This report describes the development of a nickel-cadmium Battery Interface Unit (BIU). The objective of the program was to define, develop, fabricate, and test a BIU that would reduce battery maintenance, increase battery service life, eliminate battery-related safety hazards, and provide the flight crew with meaningful battery status information. The basic program was divided into five tasks with the later addition of a sixth as follows:

- Task I - Concept Formulation
- Task II - Requirements Optimization
- Task III - Detailed Design
- Task IV - 3 Prototype BIUs
- Task V - Test and Analysis
- Task VI - Fabricate 3 Supplemental BIUs (Boosted DC-to-DC)

The first two tasks were analytical in nature and directed toward defining the advantages of a BIU in comparison with the most common battery charge approach in use on Army aircraft - constant potential charging directly from the aircraft DC bus. The results of this analysis clearly showed the superiority of using a BIU in terms of maintenance and life-cycle cost. Though there is a penalty in terms of weight and volume in comparison to constant potential charging (which requires no additional equipment), this is more than offset by cost savings and, most importantly, by improved safety.

Also as part of the analytical effort (Tasks I and II) a comparison was made of the various charge techniques that could be used for a BIU. In terms of performance and cost the multilevel, constant current charge technique was selected. A preliminary specification, included as Appendix A of this report, was developed. This specification defined the general performance criteria for the BIU.

The remainder of the basic program (Tasks III through VI) was directed toward development and evaluation of the BIU defined in the earlier tasks. Extensive testing to verify performance prediction was done. This testing involved parallel testing with batteries charged using the constant potential to provide an objective basis of comparison. The results of the tests confirmed the analytical predictions and clearly demonstrated the efficacy of using a BIU. In terms of capacity loss with cycling, the BIU demonstrated approximately a 250-percent improvement with a reduction in water loss of some 15 percent. These factors will greatly enhance onboard performance of NICAD batteries.

The sections which follow describe each of the individual tasks and the results obtained during each.

CONCEPT FORMULATION

The objective of Task I (Concept Formulation) was to identify all reasonable approaches for achieving the objectives stated in the introduction with the following constraints:

1. The unit was to be universally adaptable to present and developmental Army aircraft.

2. Only status information required for elimination of safety hazards and as an aid to maintenance was to be provided.

3. The unit was to provide a proper charge to the battery using the normal range of AC and DC voltage inputs from the bus in Army aircraft.

The candidate approaches to be considered for the BIU were identified during Task I with no attempt toward a decision on the final configuration.

The concept formulation task was divided into the following subtasks:

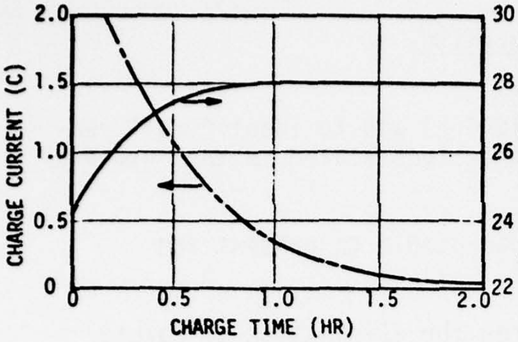
- Identification of charging approaches
- Baseline charging and monitoring requirements
- Identification of monitoring approaches
- Electrical/mechanical interfaces
- Other considerations

IDENTIFICATION OF CHARGE APPROACHES

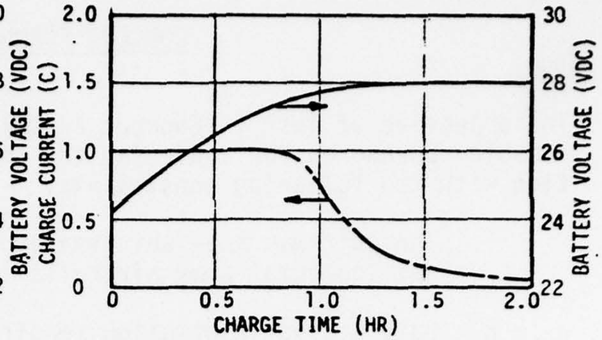
The charge approach (CA) candidates were identified and information was acquired without judgement as to applicability to Army aircraft. The numerous candidates identified were reduced to the following charging schemes:

CA-1 - Constant potential with failure protection
CA-2 - Constant current, constant potential
CA-3 - Constant current, multilevel
CA-4 - Variable frequency pulse charging
CA-5 - Constant current, variable frequency pulse charging
CA-6 - Constant current, constant frequency pulse charging
CA-7 - Constant current, constant frequency charge/discharge pulse charging

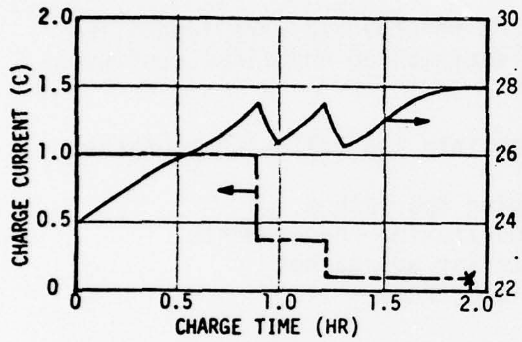
The average charge voltage/current profiles of these schemes are shown in Figure 1.



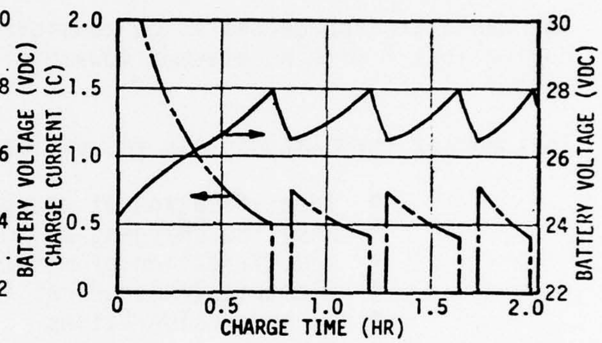
a. Constant Potential BIU (CA-1).



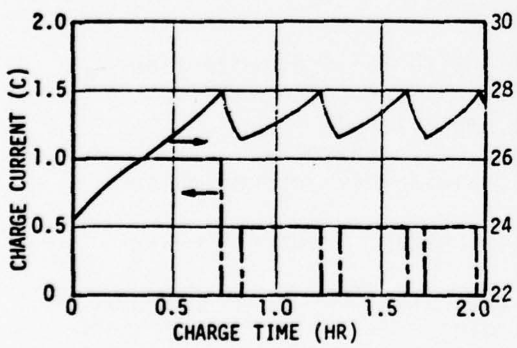
b. Constant Current, Constant Potential BIU (CA-2).



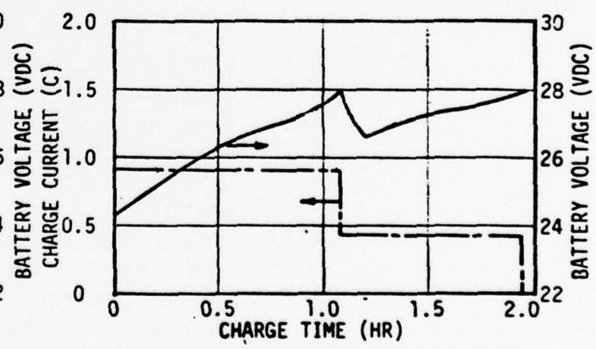
c. Multilevel, Constant Current BIU (CA-3).



d. Variable Frequency Pulse BIU (CA-4).



e. Constant Current, Variable Frequency BIU (CA-5).



f. Fixed Frequency, Constant, Current Pulse BIU (CA-6 & CA-7).

FIGURE 1. CANDIDATE BIU VOLTAGE/CURRENT PROFILES.

The voltage/current profile for the constant potential charge scheme is shown in Figure 1a. This scheme would be supplemented to provide overtemperature protection for the battery. The failure protection would not prevent overheating of the battery, but would remove the battery from the charge bus during overtemperature conditions. This would protect the aircraft and personnel against hazardous conditions.

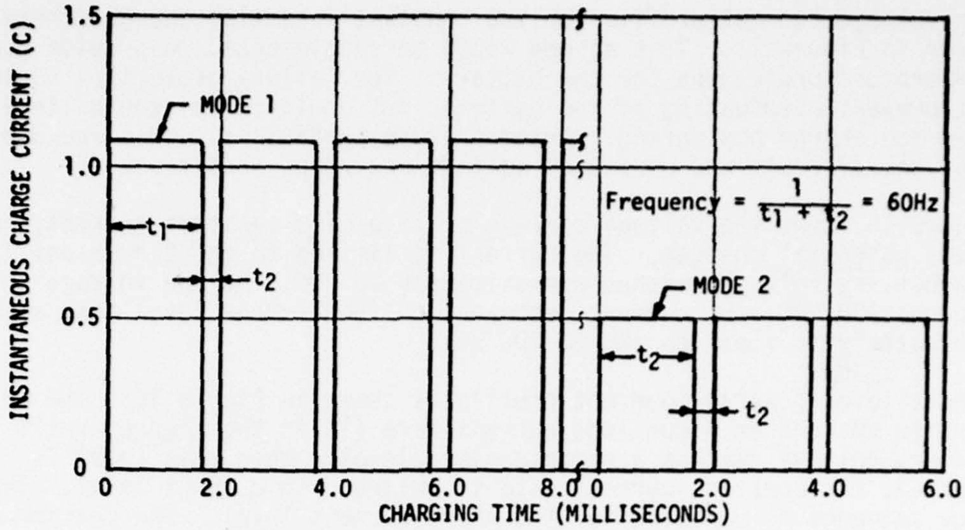
Figure 1b shows the voltage/current profile of a constant current, constant potential charger. The current is limited to the C rate until the battery voltage reaches approximately 28 VDC. As the voltage approaches 28 VDC, the current decreases to the current level that allows the battery to float on the 28 VDC bus.

A multilevel constant current profile is shown in Figure 1c. The battery is charged at a constant current rate (1C in the figure) until the battery voltage reaches a predetermined level. When this level is reached, the constant current rate is switched to a lower level. The same sequence is repeated for the third current level. The charger can be designed to cut off when the charge is completed (point X) or the battery can float on the line.

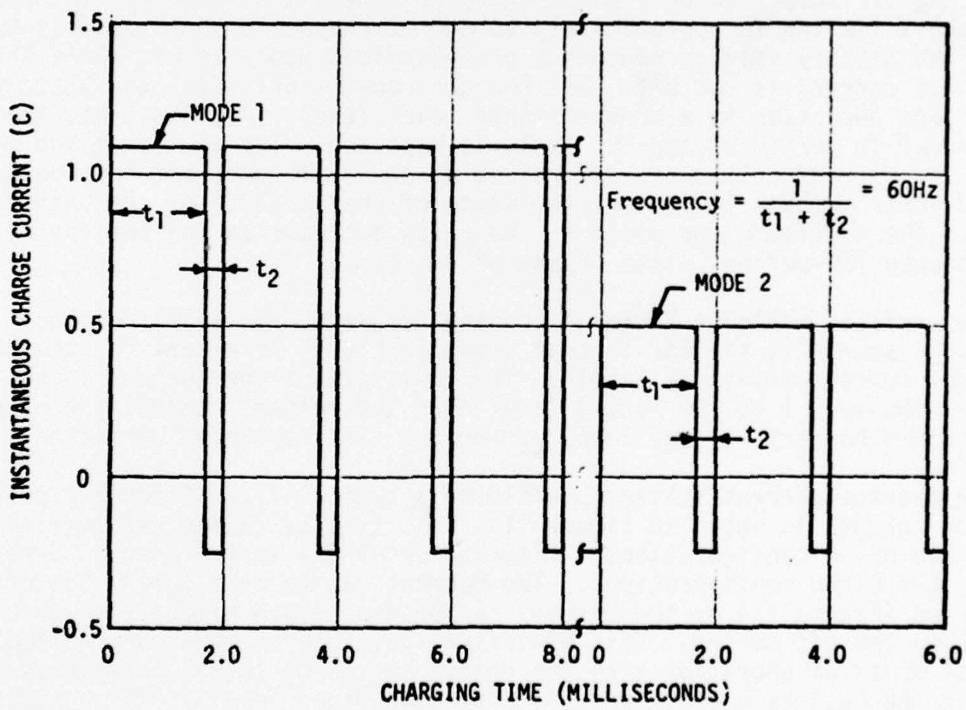
In the variable frequency pulse charging scheme in Figure 1d, the current is limited to approximately 3C and decreases to approximately 0.5C as the battery voltage reaches a predetermined upper level, where the charge current is cut off. The charger remains off until the battery voltage decreases to a predetermined lower level. At this time, the charger is turned on and the cycle is repeated. The amplitude and width of the current pulses are determined by the difference between the upper and lower voltage levels and the state of charge (SOC) of the battery. Both the amplitude and width of the pulse decrease as the battery approaches 100-percent state of charge.

The profile in Figure 1e for a constant current, variable frequency charge scheme is similar to that shown in Figure 1d except for the constant current amplitude levels. The amplitude of the current is switched from the mode 1 to the mode 2 level when the voltage reaches the predetermined battery voltage level during the first cycle of operation.

The average current/voltage profile of a typical fixed frequency pulse type charger is shown in Figure 1f. This type of charge can have either of two pulse configurations. Figure 2 shows the instantaneous current for these two configurations. The current can be zero during the off period (Figure 2a) or the battery can be discharged slightly (Figure 2b) during the off period. This system can have one or more current amplitude modes of operation with the charge switching to the next lower mode when the battery voltage reaches a predetermined level.



a. Pulse Configuration with No Discharge Between Pulses



b. Pulse Configuration with Discharge Between Pulses

FIGURE 2. INSTANTANEOUS CHARGE CURRENT PROFILE FOR FIXED FREQUENCY, CONSTANT CURRENT CHARGERS.

BASELINE CHARGING AND MONITORING REQUIREMENTS

A set of baseline charging and monitoring requirements was determined independent of the type of charger. The requirements were based on the battery characteristics and general requirements for aircraft. These baseline requirements were applied to each charge approach candidate to ensure uniformity during the Task II analysis and trade-off study.

Charging Requirements

The baseline charging requirements included definition of the following:

- Charge capability
- Maximum charge time
- Battery voltage versus temperature
- Maximum charge current
- Short/open circuit operation
- Charger cutoff signals
- Battery and charger temperature limits
- Charge limitation
- BIU efficiency

Monitoring Requirements

The baseline monitoring requirements defined the candidate parameter for monitoring in the battery system without a determination of which would be included in the BIU. The parameters included the following:

- Battery temperature
- Battery overtemperature
- BIU overtemperature
- Electrolyte level
- Cell imbalance
- State of charge (SOC)
- BIU charging status

IDENTIFICATION OF MONITORING APPROACHES

Monitoring approaches were identified for monitoring the above parameters.

ELECTRICAL/MECHANICAL INTERFACES

The following electrical and mechanical interfaces were defined as a part of the baseline applicable to each BIU charge approach candidate to be analyzed during Task II.

- Supply voltage
- Battery temperature sensor
- Cell imbalance connections
- Maintenance access
- Thermal/cooling
- Connector types
- Mounting provisions

OTHER CONSIDERATIONS

The following items were identified for consideration in the charger concept formulation:

- Packaging approach
- DC/AC power operation
- On-line/off-line charging

REQUIREMENTS OPTIMIZATION

Task II (Requirements Optimization) used the following basic ground rules:

- Characteristics and benefits were determined for all candidate BIUs.
- All candidates included cell imbalance monitoring.
- BIU optimization was based on a 20-AH on-line charger.
- Procurement cost, weight, volume, etc., were based on a preliminary design for each concept.
- Installation cost was based on a typical aircraft.
- Reliability (MTBF) was calculated using standard part count techniques.
- Estimated labor cost was computed using industrial labor efficiency rates.
- Optimum BIU selection was based on quantitative factors.

In each case, a preliminary design of the seven candidate charger types was made to the detail level and the resulting concepts were compared on the basis of weight, volume, reliability, procurement cost, installation cost, and maintenance cost (for both the BIU and the battery). In addition to this characterization of BIU candidates, the benefits of using a BIU were analyzed and a trade-off study was made of the approaches. The result of this was definition of an optimum BIU in terms of the approach to be used.

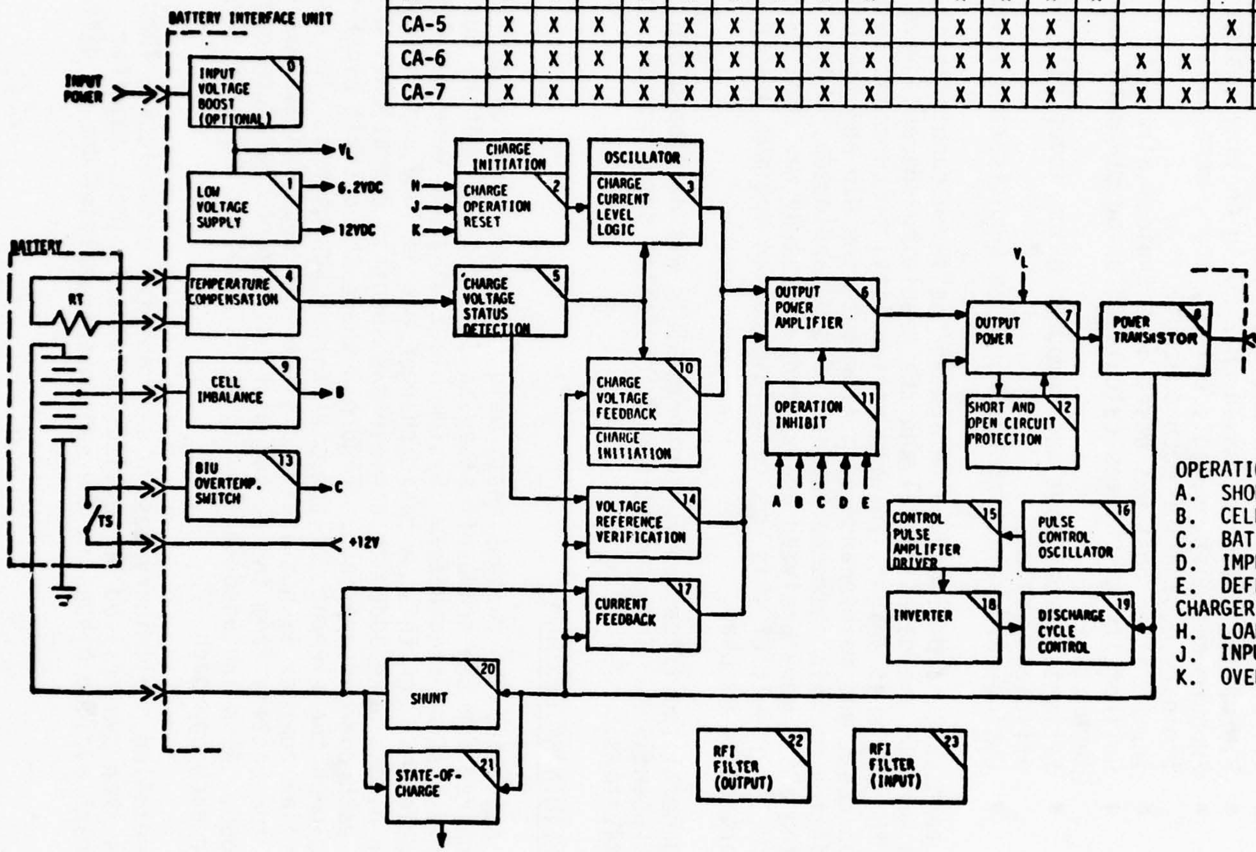
A general specification for optimum BIU's was developed and is included in Appendix A. The subsections which follow summarize the other Task II activities.

PRELIMINARY DESIGN

To determine the various cost, weight, volume, and reliability values required for the trade-off study, a detailed preliminary design was made for all seven candidates. System block diagrams were developed for each candidate. For this, a basic charger was defined and additional subsystem blocks were added to achieve the specific operationsl characteristics of each charger approach. Figure 3 shows the overall block diagram and includes the elements of the six charger approaches. The constant potential charger is not included since this approach assumes direct input to the battery from the DC bus with only overtemperature protection provided. Also included in the figure is a matrix defining the blocks used for each approach.

A detailed preliminary design was made for each block. The total design was then synthesized by putting individual blocks together. This approach avoided biases in the subsequent analyses due to differences in

CHARGER TYPE	FUNCTIONAL ELEMENT USAGE																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
CA-2	X			X	X	X	X	X	X	X	X	X	X				X			X	X		
CA-3	X	X	X	X	X	X	X	X	X		X	X	X				X			X	X		
CA-4	X	X		X	X	X	X	X	X		X	X	X	X						X	X	X	
CA-5	X	X	X	X	X	X	X	X	X		X	X	X				X			X	X	X	
CA-6	X	X	X	X	X	X	X	X	X		X	X	X		X	X				X	X	X	X
CA-7	X	X	X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X	X	X



KEY

OPERATION INHIBIT SIGNALS
A. SHORT CIRCUIT
B. CELL IMBALANCE
C. BAT OR BIU OVERTEMP
D. IMPROPER INPUT VOLTAGE
E. DEFECTIVE BAT TEMP SENSOR

CHARGER OPERATION RESET SIGNALS
H. LOAD REMOVED
J. INPUT POWER CORRECTED
K. OVERTEMP COND CORRECTED

FIGURE 3. COMPOSITE BIU BLOCK DIAGRAM.

design approaches from manufacturer to manufacturer.

CHARACTERIZATION OF CANDIDATE APPROACHES

The characterization of the candidate approaches consisted of definition of the volume, weight, reliability, procurement cost, installation cost, and BIU maintenance cost. Table 1 summarizes the results of this analysis. The following subsections describe the methods used to determine each of the parameters.

TABLE 1. BIU CHARACTERIZATION DATA.

BIU Candidate No.	Weight (lb.)	Volume (cu.in.)	Reliability (MTBF)	Procurement Cost ($)		Installation Cost ($)	BIU Maint. Cost ($/yr)
				100 Unit Quantity	1000 Unit Quantity		
CA-1	0.65	13.25	89,870	236.00	177.00	133.00	0.68
CA-2	9.50	400	10,848	598.79	514.07	181.00	5.65
CA-3	9.60	400	9,948	623.98	535.37	181.00	6.16
CA-4	9.73	400	10,336	634.49	544.63	181.00	5.93
CA-5	9.73	400	9,881	647.88	555.84	181.00	6.20
CA-6	9.93	400	9,538	662.69	569.88	181.00	6.43
CA-7	9.93	400	9,265	665.17	574.02	181.00	6.62

Volume

The volume was determined by defining a maximum volume for the BIU and assuming it would be the same regardless of which candidate approach was used. Thus none of the candidate approaches was biased by volume considerations. This approach was valid since the slight difference in volume of components from candidate to candidate is readily accommodated by the packaging configuration rather than increased volume.

Weight

The weight of the candidates was estimated by summing the weights of major components from the preliminary designs. The actual weight of a prototype model of a constant current charger similar to candidate CA-3 was used as the baseline in estimating the weights. The baseline weight

was adjusted for the other candidates in accordance with the addition or deletion in major components from candidate CA-3 in the preliminary designs. Components such as switching transistors, integrated circuits, and small resistors were not considered as major components.

Reliability

The reliability figures were calculated for each of the preliminary designs using the parts count reliability prediction technique delinated in MIL-HDBK-217B. The equation used to calculate the failure rate is

$$\Lambda_{P(T)} = \sum_{i=1}^{K} \Lambda_{P(i)}, \quad \Lambda_{P(i)} = \sum_{i=1}^{K} N_i \, \Pi_{Q(i)} \Lambda_{G(i)} \Pi_{L(i)}$$

where $\Lambda_{P(i)}$ = total failure rate of a system, subsystem, or design block

N_i = quantity of the i-th generic part

$\Pi_{Q(i)}$ = quality factor for the i-th generic part

$\Lambda_{G(i)}$ = generic failure rate for the i-th generic part

$\Pi_{L(i)}$ = learning factor applicable to integrated circuits only; for other parts this factor drops out of the equation

The following assumptions were made during the reliability computations:

- All parts are MIL-SPEC.
- The environment is an aircraft uninhabited (not in cockpit).
- $\Pi_L = 1$ and $\Pi_Q = 2.5$ for all integrated circuits.
- $\Pi_Q = 0.25$ for all diodes and transistors.
- $\Pi_Q = 1$ for all other parts.

The failure rate was calculated for each block shown in Figure 3. The system reliability was then determined by summarizing the reliability of each block in accordance with the matrix in Figure 3.

Procurement Costs

The procurement costs to the Army were estimated for quantities of 100 and 1,000 units. The cost of material (components, etc.) and that associated with manufacture, test, checkout, and delivery of hardware was included. Nonrecurring costs such as initial design and qualification are omitted from the estimates.

The part and material cost estimates were obtained by summing the cost of the component parts for each approach. The manufacturing labor costs were determined by summing the estimated labor cost required to fabricate, assemble, test, and check out each candidate BIU. The estimated labor costs associated with assembly, test, and checkout differ slightly in proportion to the increase or decrease in the complexity of the design approach.

Each of the estimated labor costs was computed by using industrial efficiency and labor rates. A markup of 20 percent was also included.

Installation Costs

The installation costs were determined by estimating the cost of installing the BIUs on a typical aircraft. The installation costs were assumed to be the same for all candidates except the CA-1. The installation cost for the CA-1 is the cost of installing the battery overtemperature protection device in a typical aircraft. The UH-IH helicopter was used for estimating the typical aircraft installation costs.

BIU Maintenance Costs

The maintenance cost estimates were calculated by dividing the number of hours in a year by the MTBF, assuming a MTTR of 0.5 hour and military labor efficiency rates. Hours per year was used rather than flight hours to allow lumping maintenance factors not considered in the part count MTBF such as random failure, scheduled maintenance, and shelf life.

It is recognized that the maintenance cost figures using this estimating technique contain inaccuracies. However, consistent application of this technique to all candidates leads to relative accuracy in the estimates. Consequently, the trade-off study is not biased by cost estimate inaccuracy.

The maintenance cost estimates were calculated using the following equation:

$$\frac{8{,}760}{\text{MTBF}} \times 0.5 \times 14.00 = \text{Maintenance Cost Per Year}$$

ESTIMATED BIU BENEFITS

A decision as to whether to use a BIU made strictly on the basis of the characteristics of the candidates as defined previously would favor the constant potential charger. Any BIU weighs more, occupies more volume, and costs more to procure and install than the constant potential approach now in use. The BIU is attractive because of the long-term benefits afforded by lower maintenance cost, longer battery life, and im-

proved safety. These facets more than offset the increased weight, volume, and initial costs for the system.

Better control of charge and provision for overtemperature protection will eliminate virtually all problems with thermal runaway of nickel-cadmium batteries. Though this will, in itself, result in significant cost savings, it is of paramount importance because it removes an existing hazardous condition. The major cost impact will be in the area of maintenance. Longer periods between scheduled maintenance and drastic reduction of removals arising from battery problems will definitely reduce the cost of maintaining a NICAD battery on an aircraft. The bulk of the analysis described in this subsection was concentrated in this area. The results of the analysis, summarized in Table 2, show that any of the BIU candidates is vastly superior to the constant potential system now in use.

Baseline Battery Maintenance

The only baseline to which the BIU can be compared is the maintenance associated with the present approach to battery charging (i.e., no charger at all). As long as the battery is on board the aircraft and functioning normally, maintenance is slight. Only when the battery is removed for some reason does cost become a significant factor. The nature of nickel-cadmium batteries is such that they must be reconditioned periodically. In addition, battery removals occur at other times because some problem develops. For the analysis, both the scheduled and unscheduled removals were considered separately and then combined to yield a total figure.

The Technical Manual for aircraft nickel-cadmium batteries[1] spells out normal battery maintenance actions. Each week, or every 25 flight-hours, onboard preventive maintenance is to be accomplished, and every 120 days or 100 flight-hours the battery is to be removed for servicing (reconditioning). Since the flight program for most Army aircraft is 240 flight-hours per year[2], time rather than the number of flight-hours will govern scheduled maintenance. By this approach, there will be approximately three scheduled removals each year and some 49 onboard inspections. This represents peacetime conditions, and in an active combat environment, 660-840 flight-hours per year will occur. For this study, the more conservative peacetime figures were used.

The frequency of unscheduled removals for batteries is not a single term that is generic for all applications. For aircraft where the battery is

[1]Technical Manual, TM 11-6140-203-15-2, OPERATOR'S, ORGANIZATIONAL, DS, GS, AND DEPOT MAINTENANCE MANUAL INCLUDING REPAIR PARTS AND SPECIAL TOOLS LISTS: AIRCRAFT NICKEL-CADMIUM BATTERIES, Headquarters, Department of the Army, Washington, D. C., 1 December 1969.

[2]Field Manual, FM 101-20, UNITED STATES ARMY AVIATION PLANNING MANUAL, Headquarters, Department of the Army, Washington, D. C., 27 February 1976.

TABLE 2. ESTIMATED BIU BENEFIT SUMMARY.

Concept	BIU Benefit and/or Improvement					
	Time Between Scheduled Bat. Removals	Avg. Time Between Unsched. Removals (days)	Avg. Battery Maint. Cost ($/flt-hr)	Period for BIU to Payout Total Cost (flt-hr)	Frequency of Onboard Inspections	Safety
CA-1 (Present Syst.)	100 hrs or 120 days	140	4.74	-	25 flt-hr or weekly	No change from present
CA-1 (With Overtemp. Protection)	100 hrs or 120 days	140	4.74	-	25 flt-hr or weekly	All BIU candidates and the constant potential system with overtemperature protection will eliminate catastrophic failure of battery due to thermal runaway.
CA-2	140 days	315	1.82	275	Only as required	
CA-3	180 days	400	1.43	240	Do	
CA-4	140 days	320	1.80	267	Do	
CA-5	140 days	335	1.77	270	Do	
CA-6	160 days	350	1.62	265	Do	
CA-7	160 days	350	1.62	265	Do	

used only for emergency power or to supply small loads for short periods, the frequency of unscheduled removals is relatively low. For aircraft where energy for frequent engine starts or other large loads is regularly supplied by the battery, battery replacements are much more frequent. To account for this variation from application to application, a range of 60-140 flight hours between unscheduled removals was assumed for the constant potential charging system. This spread is consistent with actual experience for a variety of Army aircraft.

There is a second aspect of the maintenance associated with unscheduled

removals. The basis used for the analysis was the experience of United Airlines over a 1-year period (data from Army records would be per preferred, but such information was not readily available). The United Airlines data is based on experience with a large fleet of aircraft, and it was assumed that the mix for Army aircraft would be similar. Table 3 summarizes the unscheduled removals and the reasons for removals. The data in this table were used as the baseline for the study.

TABLE 3. BASELINE UNSCHEDULED BATTERY REMOVALS PER YEAR.

Reason for Removal	Percent of Total
Low Voltage	32.0
Dry Cells	5.4
Overheating	19.7
Electrolyte Spewage	15.0
Electrical Leak	10.0
Other	17.9
Total	100.0

Battery Maintenance Improvement with BIU

Each BIU approach investigated in this study does reduce both the scheduled and unscheduled maintenance associated with aircraft nickel-cadmium batteries. The magnitude of such improvement, however, differs from concept to concept.

Scheduled Maintenance - The frequency of reconditioning NICAD batteries as defined in the Technical Manual is based on the time for the battery to drop below 1.0 volt per cell during discharge. Test results with several of the BIU candidates show a definite improvement in this area. The control of the input to the battery and temperature-compensated charging leads to better balance between cells and a greater number of cycles before the voltage drops to the 1.0 volt per cell lower limit. The need for the 25 flight-hour/weekly inspection is also greatly reduced since all of the concepts considered are instrumented. Thus, there will be a need to check the battery only when there is a malfunction.

Unscheduled Maintenance - The reduction in unscheduled maintenance afforded by any of the BIU concepts can also be traced to the fact that input power to the battery on charge is better controlled and temperature compensated. Thus, cell imbalance, water boil-off, and electrolyte spew-

age will be greatly reduced. The occurrence of thermal runaway will be virtually eliminated by the better control of input power and by the overtemperature limiting features incorporated in the candidate systems. Cell failure which can manifest itself in electrical leakage, excessive water loss, overheating, low battery voltage, or electrolyte spewage will be reduced because the cells will be charged properly and not overstressed.

Battery Maintenance Cost

The preceding subsections defined both scheduled and unscheduled battery maintenance in terms of occurrences per year. There is, however, another part to the story - the labor cost associated with each occurrence. For this, a battery maintenance model was developed. This model, shown in Figure 4, includes actions at all three levels of maintenance: unit (AVUM), intermediate (AVIM), and depot.

The individual actions (represented by the boxes in Figure 4) are as defined in TM11-6140-203-15-2 and show the actions to be accomplished at each level. Above each block is a number representing the number of man-hours required to accomplish the effort. These values are based on data obtained from various sources, including data collected by the Navy under its 3M program. As an example, the 3M data showed 9.735 man-hours were required at the intermediate level of maintenance, which is the total time shown in the model. Though the times for individual batteries and aircraft types may differ from those shown, use of the same data for each candidate BIU (and for the baseline system) does yield consistent results.

For a given battery population, the percentage through each action varies with whether it is scheduled or unscheduled. Also, there is variation arising from whether a BIU is used on the aircraft and the type of BIU employed. Each candidate approach was analyzed in terms of the model. Table 4 summarizes this analysis.

TABLE 4. MAINTENANCE MAN-HOURS REQUIRED PER BATTERY PER ENTRY

CONCEPT	SCHEDULED MAINTENANCE	UNSCHEDULED MAINTENANCE
CA-1	5.145	5.753
CA-2	2.839	8.250
CA-3	2.839	8.268
CA-4	2.839	8.224
CA-5	2.839	8.224
CA-6	2.839	8.224
CA-7	2.839	8.224

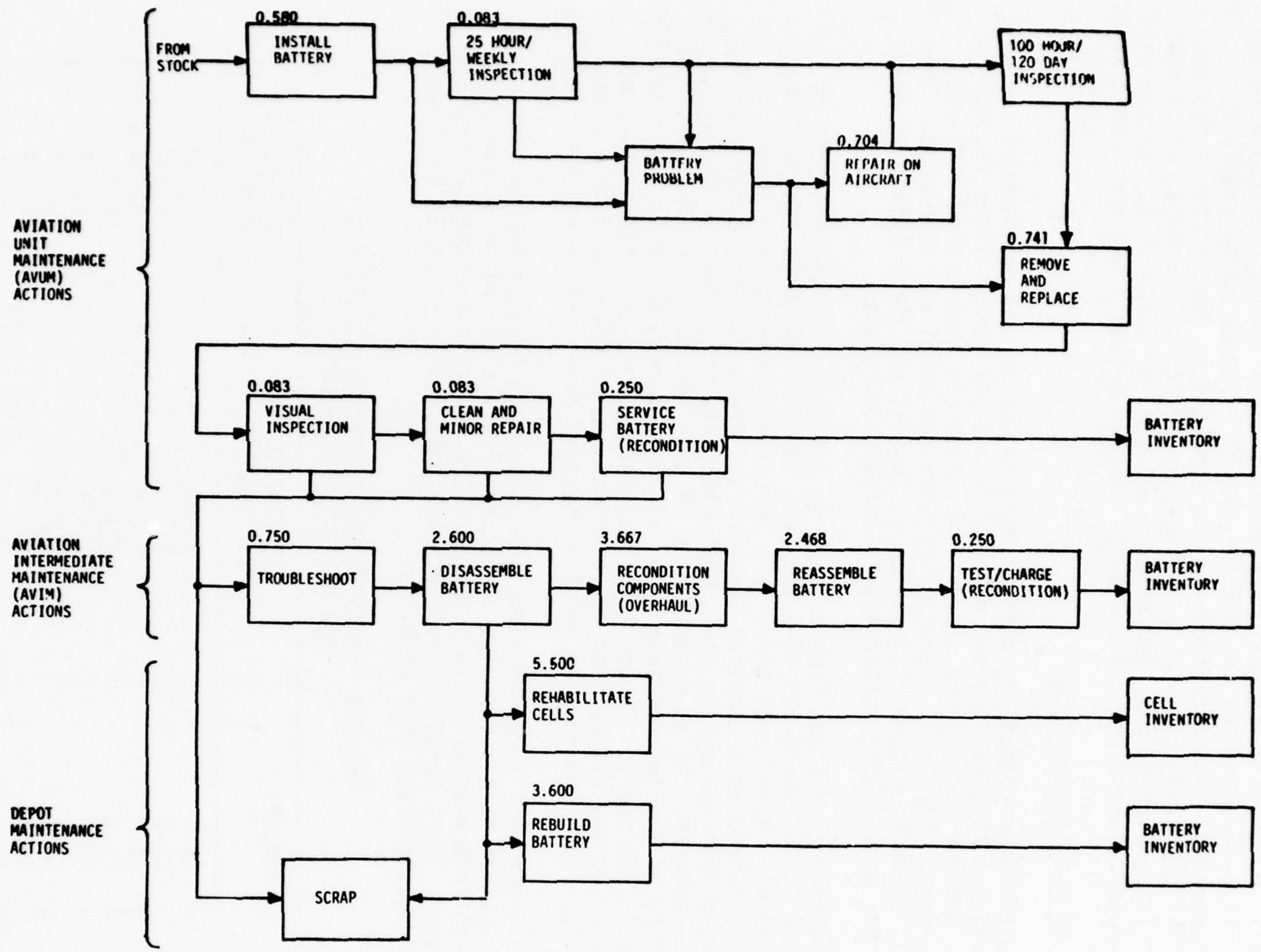


FIGURE 4. BATTERY MAINTENANCE FLOW SEQUENCE.

As can be seen from Table 4, there is a substantial reduction in the man-hours required for scheduled maintenance when a BIU is used. This is due to the lessening of battery problems and the resultant increase in the number of batteries that will require only reconditioning. The man-hours per unscheduled maintenance action increases when a BIU is used. The major reason for this is a reduction in the number of cells that must be scrapped. Thus, there are more cells going through maintenance at the intermediate level and repair is more costly in labor than replacement.

The yearly maintenance cost for a nickel-cadmium battery is the product of the number of actions required and the man-hours required per action, at a representative rate. For this study a rate of $14 per hour was used. This rate was obtained from the AVRADCOM Cost Analysis Branch as being typical for Army estimating purposes.

Maintenance cost must also include the cost of material. For this study, this is assumed to be the cell cost ($27.17 each). The number of cells that must be replaced is represented in the model as scrap. This includes cells replaced because of life (40 months) and due to problems that cannot be remedied within one of the levels of maintenance. Also for this study, a 19-cell battery was assumed. Table 5 is a summary of the yearly battery maintenance cost including both material and labor.

TABLE 5. YEARLY BATTERY MAINTENANCE COST - TOTAL

Concept	Average (1) Cost/Year($)	Average $/Flt-Hr
CA-1	1,138.46	4.74
CA-2	438.03	1.82
CA-3	343.16	1.43
CA-4	433.08	1.80
CA-5	425.85	1.77
CA-6	388.82	1.62
CA-7	388.82	1.62

(1) The average equates to a period between removals (baseline) of approximately 92.5 flight hours for all concepts.

As can be seen, any of the BIU concepts (CA-2 through CA-7) offers dramatic improvement in the cost of battery maintenance when compared to the present constant potential system (CA-1). The multistep constant current (CA-3) system shows the most improvement. The table reflects peacetime operation of 240 flight-hours per year. Even greater cost savings would accrue in a combat environment where the number of flight-

hours per year is tripled.

Analysis of Life-Cycle Costs

Though there is a clear advantage for any BIU over the present battery charging technique in terms of maintenance cost, the question still remains as to whether the savings in maintenance cost offsets the cost penalty for buying and installing a BIU.

For the constant potential system, two cases must be considered. Present aircraft charging schemes involve supply of battery charging power directly from the DC bus with no provision for limiting an overtemperature condition (Case 1). There are strong indications that some form of protection will be installed (Case 2). If the latter does occur, there will be some procurement and installation cost associated with the use of such a device. For this study both cases were considered.

As has been noted previously, there is variation in the rate of unscheduled removals between various aircraft types. For aircraft where the battery is used only for emergency or backup power, the frequency of removals is lower than for aircraft where the battery is heavily used for such things as engine starting. The sensitivity of the results of the life cycle cost analysis to the various aircraft is also important to consider. Figure 5 shows this sensitivity. The cost is presented for three different periods between unscheduled removals for the baseline system (60, 100, and 140 flight-hours). The constant potential system and the systems with the highest (CA-2) and lowest (CA-3) operating cost are depicted. The crossover points are circled.

As can be seen from Figure 5 for the range of unscheduled removals considered, the BIU still offers operational cost savings. Even for the case of 140 flight-hours for the least cost effective system (CA-2) the BIU pays for itself after approximately 340 flight-hours - less than 18 months. For aircraft that now experience high battery failure rates, the crossover is approximately 6 months.

Other Considerations

Of major concern is the hazard associated with nickel-cadmium battery explosions or fires. On present aircraft, there is always the possibility that thermal runaway will occur. This condition, if not corrected, can lead to total loss of the aircraft in the extreme case. During a 4-year period at Fort Rucker, Alabama (1969-1972), an average of 3.5 cases of battery explosion or burning occurred each year. This data was only for the BB-433/A battery (UH-1) and at only one location. A great many more such incidents could be projected on a service-wide basis.

Catastrophic failure where the loss of an aircraft results from thermal

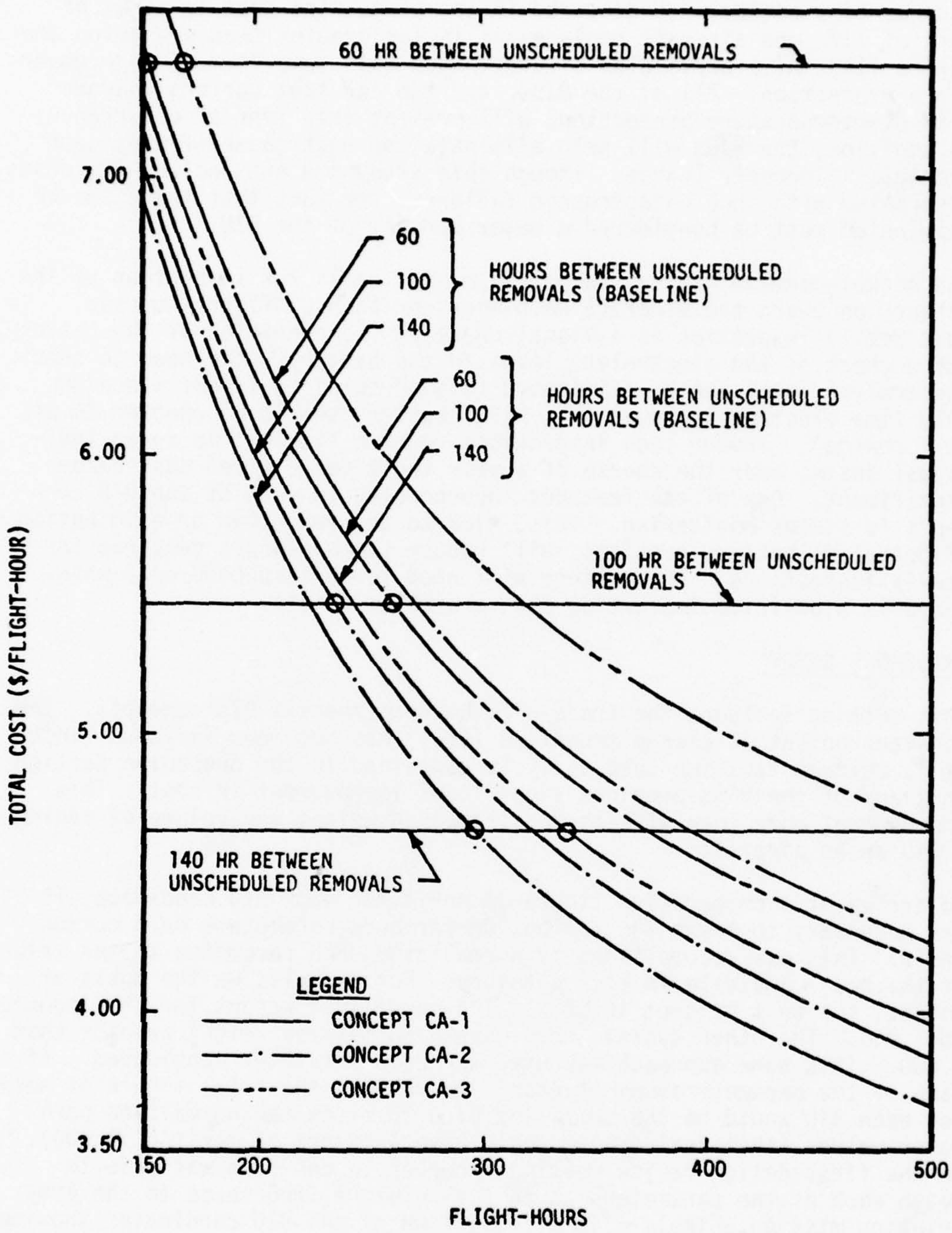


FIGURE 5. BATTERY SYSTEM LIFE-CYCLE COST SENSITIVITY.

runaway of a battery has occurred in the past. The cost in terms of loss of life and aircraft replacement is far greater than equipping the entire fleet of a particular aircraft type with some form of overtemperature protection. All of the BIUs, and the constant current charger with overtemperature protection, will prevent this type of occurrence. In addition, the BIUs will help eliminate the root cause of many such problems - improper charge. Though this study did not include the costs associated with such catastrophic failures, the fact that these can be eliminated must be considered a major benefit of the BIU.

The nickel-cadmium battery technical manual calls for inspection of the battery on board the aircraft each week (or each 25 flight-hours). This weekly inspection is a visual check of the condition of the battery and a check of the electrolyte level in the battery. The need to check electrolyte level can be eliminated (a good thing in itself since the only time electrolyte level in a NICAD battery should be checked is at full charge). Though such inspections require little time on an individual basis, over the course of a year the time required does become significant. One of the features incorporated in each of the BIU concepts is status monitoring. This, tied to the reduction or elimination of potential battery problems, will reduce the man-hours required for weekly inspections. The battery will need to be inspected only when there is a positive indication that a problem exists.

TRADE-OFF STUDY

This section includes the trade-offs between the six BIU concepts. The constant potential charge technique (CA-1) has not been included since it is evident from the cost analysis contained in the preceding section that any of the BIUs provides significant improvement in cost. This improvement more than offsets the increased weight and volume of adding a BIU on an aircraft.

To arrive at a comparative figure of merit for each BIU candidate, it was necessary to treat the various performance parameters on a common basis. This was accomplished by normalizing each parameter to the value of the best candidate in each category. For example, on the basis of weight, the best concept is CA-2. The normalized weight for this concept is 1.000. The other systems then have a normalized weight greater than 1.000. This same approach was used for each parameter considered. If each of the parameters were of equal importance, the total figure of merit for each BIU would be the summation of 0.20 times the normalized parameter values (the ideal system would have a figure of merit of 1.000). In the first design review meeting, however, a decision was made to weigh each of the parameters as to its relative importance to the Army aviation mission. Table 6 is a comparison of the BIU candidates showing both the actual and normalized value for each parameter and the weighing factors determined during the design review.

TABLE 6. BIU COMPARISON SUMMARY

Weighting Factor	Parameter	CA-2	CA-3	CA-4	CA-5	CA-6	CA-7
	BIU Wt (Lb)	9.50	9.60	9.73	9.73	9.93	9.93
	Normalized Wt (W_N)	1.000	1.010	1.024	1.024	1.045	1.045
0.30	Weighted W_N	0.300	0.303	0.307	0.307	0.314	0.314
	BIU Vol (In.^{3})	400	400	400	400	400	400
	Normalized Vol(V_N)	1.000	1.000	1.000	1.000	1.000	1.000
0.10	Weighted V_N	0.100	0.100	0.100	0.100	0.100	0.100
	BIU Failures/ Million Flt-Hr	92.18	100.52	96.75	101.20	104.84	107.93
	Normalized Fail. Rate (M_N)	1.000	1.090	1.050	1.098	1.137	1.171
0.10	Weighted M_N	0.100	0.109	0.105	0.110	1.114	0.117
	BIU Production Cost 1000 Unit ($)	436	454	462	471	484	484
	BIU Installation Cost ($)	181	181	181	181	181	181
	Total Fixed Cost ($)	617	635	643	652	665	665
	Normalized Fixed Cost ($)	1.000	1.029	1.042	1.057	1.078	1.078
0.25	Weighted C_{FN}	0.250	0.257	0.260	0.264	0.270	0.270
	BIU Maint Cost ($/Flt-Hr)	0.023	0.026	0.025	0.026	0.027	0.028
	Bat Maint Cost ($/Flt-Hr)	1.825	1.430	1.804	1.774	1.620	1.620
	Total Maint Cost ($/Flt-Hr)	1.848	1.456	1.829	1.800	1.647	1.648
	Normalized Maint Cost (C_{MN})	1.269	1.000	1.256	1.236	1.131	1.132
0.25	Weighted C_{MN}	0.317	0.250	0.314	0.309	0.283	0.283
	Total Weighted Values	1.067	1.019	1.086	1.090	1.081	1.084

As can be seen, the multilevel constant current system (CA-3) appears to be the best BIU candidate. This system is far superior to the other candidates in terms of maintenance cost and it is toward the lower end of the range in terms of the other parameter values. The second best system is the constant current/constant potential system. Though the mainten-

ance cost is higher than that of the other concepts, the relative simplicity of this approach offsets this to a degree.

To determine the sensitivity of the comparison to the accuracy of the actual values for each parameter, weight, volume, failures, fixed cost, and maintenance cost were increased by 15 percent for concept CA-3. The actual values for the other concepts were left the same. The final figure of merit changed under these conditions, but it is important to note the order of preference did not change.

A second area where the question of sensitivity arises is the weight assigned to each parameter. For this analysis, each parameter in turn was given a weighing factor of 0.500 with the other parameters assigned a weight of 0.125. With one exception, the results of this analysis remained the same as the original. The only exception came when reliability was weighed at 0.500. In this case, concept CA-2 appeared marginally better.

The basic analysis clearly shows that the multilevel, constant current system is the best of the BIUs considered. Further, selection of this candidate is relatively insensitive to parameter variation. For the remainder of the program therefore, effort was concentrated on this system.

Although the BIU trade-off study was based on operation from the 28 VDC bus without voltage boost, other input and output power options were considered. The option of integrated packaging (BIU with battery) was also considered.

DESIGN AND FABRICATION

Tasks III, IV, and VI involved the design and fabrication of the BIU selected as the most promising - the multilevel, constant current approach. Three chargers, that operate directly from an AC input, were designed (Task III) and fabricated (Task IV) and three additional chargers that operate from a 28 VDC input were designed and fabricated (Task VI). For the latter, an internal boost circuit was included to provide a maximum charge voltage of 31.5 VDC to the battery. The basic design of each type of BIU is the same and it is only with the input circuitry where differences occur. The subsections that follow discuss both types.

BIU DESIGN

The BIU was designed to meet the performance requirements of the general BIU specification included in Appendix A. The AC input units are Class III and the DC input units are Class II per the specification.

Operational Characteristics

The BIU provides charging current at three constant-current levels. The typical charge current and voltage profile as a function of time is shown in Figure 6. The charger operation in the four current level modes is as follows:

Mode A -- Constant current at 1C rate until the battery voltage reaches the predetermined, temperature-compensated level.

Mode B -- Constant current at 0.4C rate until the battery voltage reaches the predetermined, temperature-compensated level.

Mode C -- Continuous constant current at 0.05C rate.

Mode D -- Charging current turned off at point "X" in Figure 6. This mode was used during early BIU performance tests.

The predetermined voltage level is a temperature-compensated voltage of the value required for proper charge of the battery under various temperature conditions. The charge voltage level versus temperature is shown in Figure 7.

Each time battery charging is initiated, the charger automatically cycles to Mode A and progresses to Mode C. The continuous 0.05-0.07C charge rate in Mode C is the trickle or topping level optimized for maximum battery charge retention and minimum water loss. This level was determined

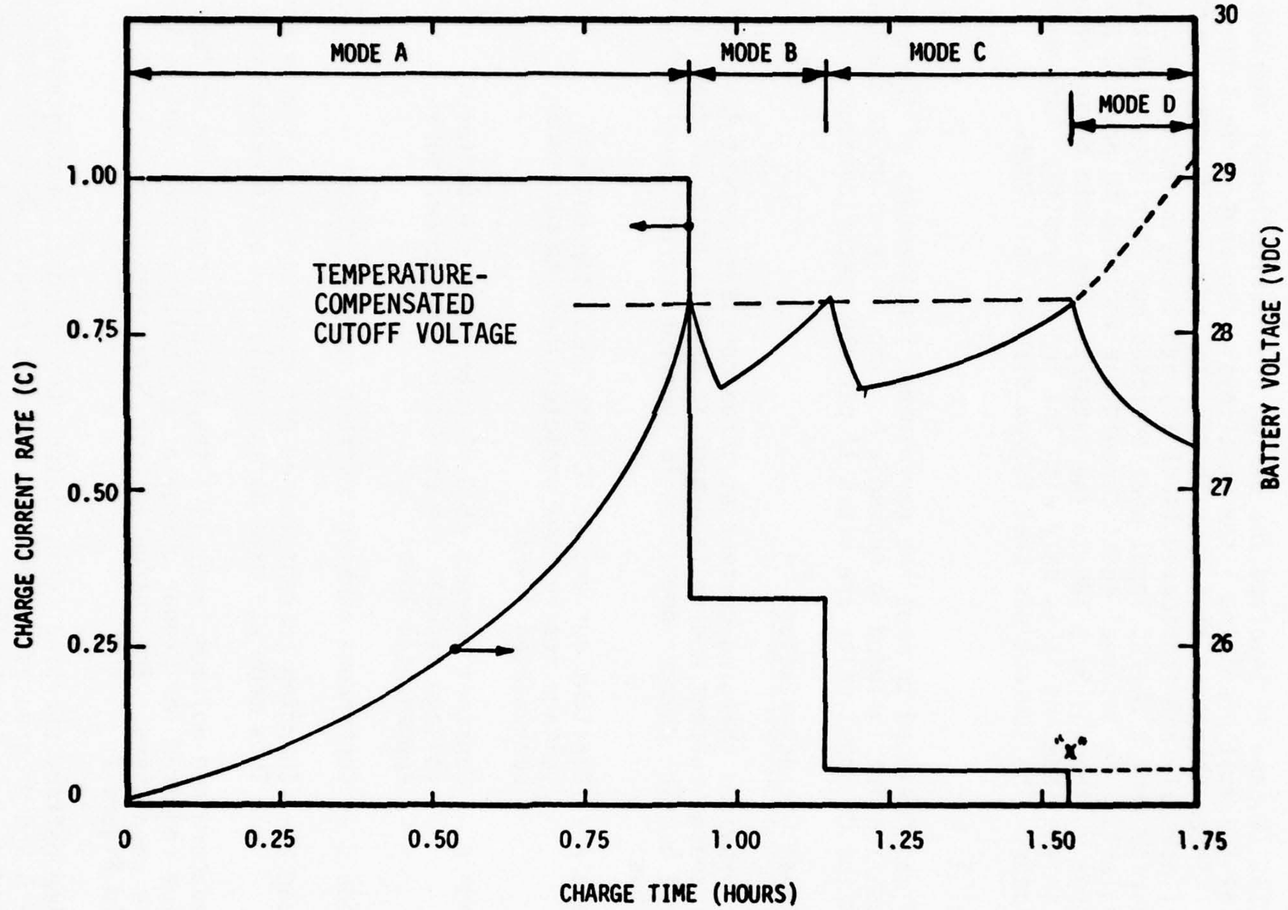


FIGURE 6. TYPICAL CHARGE CURRENT/VOLTAGE PROFILE.

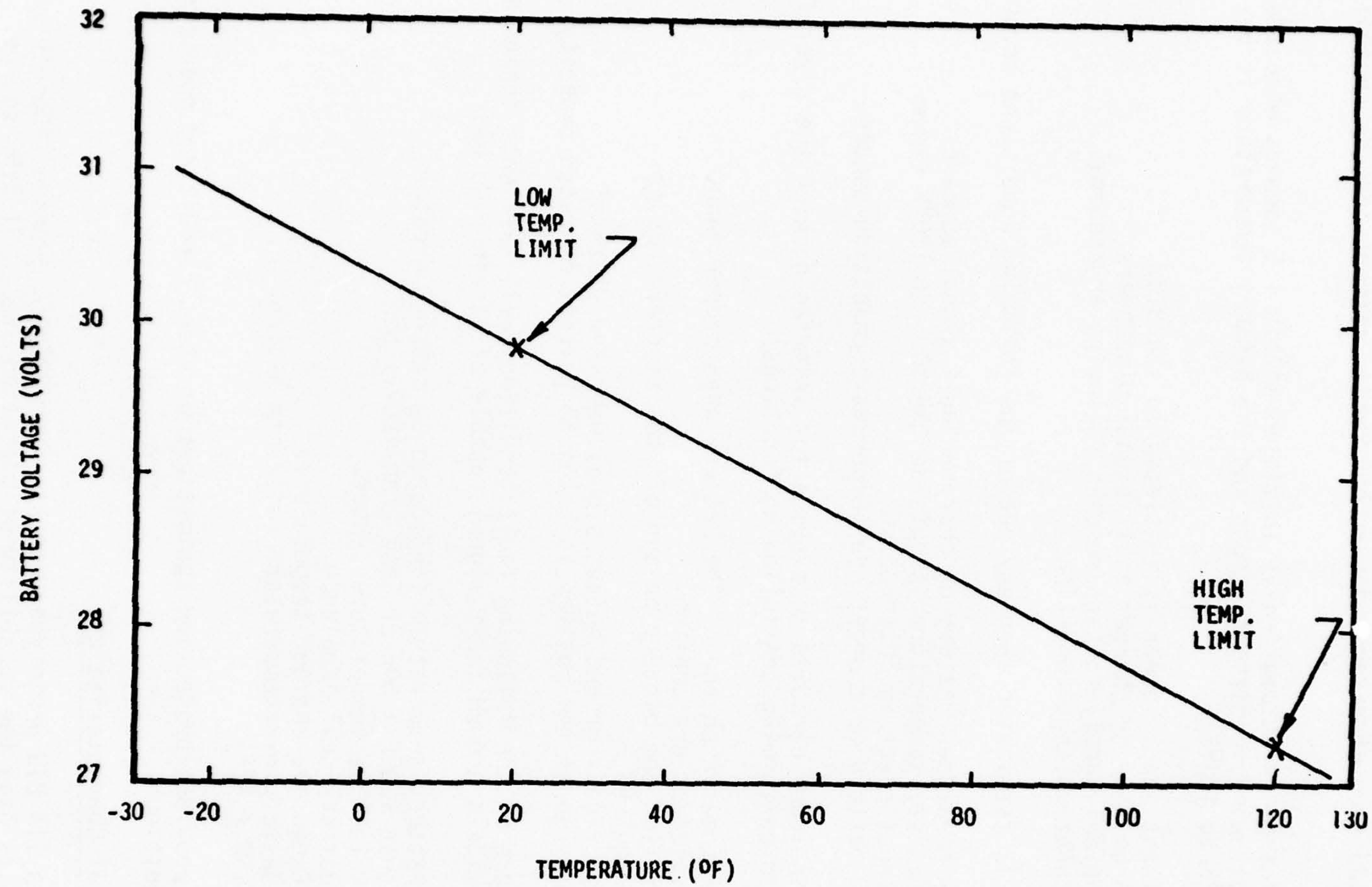


FIGURE 7. BATTERY CHARGE VOLTAGE VERSUS TEMPERATURE.

during the cycle testing in Task V where over 225 cycles were completed without addition of water and over 500 cycles without battery reconditioning.

Battery charge is automatically initiated within 1.5 seconds when one of the following conditions occurs and the battery temperature is between 20^oF to 120^oF:

- Input supply power is initiated to the BIU.
- A battery or charger fault signal disappears.
- Normal supply voltage resumes following an abnormal input voltage condition.

Charging is terminated when any one of the following conditions occurs:

- A hazardous battery or charger fault signal appears.
- Battery temperature is outside the 20^oF to 120^oF range.
- Input power is interrupted.
- A battery or charger overtemperature condition occurs.

The BIU includes circuits to provide for interfacing with the aircraft system and performing the following functions:

- Automatic charge of the battery when proper input voltages are applied.
- Switch the battery on and off the aircraft bus as required.
- Provide a ground output signal when the state of charge of the battery is below 50 percent of rated capacity.

One or more of the following fault conditions will terminate charge and will provide a ground fault signal capable of sinking 100 mA:

- Battery temperature (indicated by sensor) greater than $120^oF \pm 5^oF$ or less than $+20^o \pm 5^oF$.
- Defective temperature sensor.
- Battery cell imbalance.
- Excessive charger temperature.
- Battery overtemperature (discrete switch 150 ± 5^oF).

The BIU provides protection against output short circuit and open circuit conditions.

Electrical Characteristics

The class III BIU prototypes operate from 220VAC, 3-phase, 400-Hertz input. These units have the capability of operating from a 31.5VDC source. The

Class II prototypes operate from a 28 VDC source. A block diagram of the Class III BIU is shown in Figure 8 while a block diagram for the Class II BIU is shown in Figure 9.

The constant current for battery charge, in either case, is controlled by the output current amplifier which drives a power transistor used as a dissipative series regulator. The output amplifier is driven by the current feedback amplifier. Charge is inhibited in the charger by inhibiting the output of the output current amplifier.

The charge voltage status detection and the charge initiation/reset circuits generate the charge and voltage detection signals required to produce the tri-level constant current charge profile. The temperature compensation circuit generates the temperature compensated charge voltage reference and the charge termination signals for high and low battery temperature conditions.

The cell imbalance circuit detects battery cell imbalance to determine cell failure. The fault indicator circuitry generates the Go/No-Go fault indication signals for abnormal battery and no-charge conditions.

The relay control circuitry senses the input bus voltage and switches the battery off-line for charging or on-line as battery power is required by operational conditions.

Detail schematics of the electronic circuitry for each type of BIU are shown in Figures 10 and 11. Figure 10 is for the AC input charger and Figure 11 is for the DC input unit. The charge current level logic contains CMOS flip-flops that are reset to Mode A by the reset circuit at power turn-on and generates the three current reference voltage levels as the state of the flip-flops is changed by the charge voltage and status detection circuitry. The CMOS inverters are part of the oscillator clock circuit which clock the flip-flops to prevent circuit operation due to transients in the system. The temperature compensation circuit uses a 6.8 K-ohm positive coefficient linear temperature sensor in the battery to generate a voltage reference with an accuracy of three percent or better.

Circuitry for monitoring cell imbalance, temperature sensor failure, and caution/advisory panel Go/No-Go status signals is also shown on the schematics. The cell imbalance circuit compares 10/9 times the voltage of the upper 9 cells in the battery to the voltage of the lower 10 cells and generates a fault signal when the difference between the two voltages indicates a cell failure (approximately 1.3 $\pm$ .3 VDC).

The transformer/rectifier circuit, output power transistor, printed circuit board interface, and other housing assembly circuitry is shown in Figures 12 and 13 for the AC and DC input BIUs respectively.

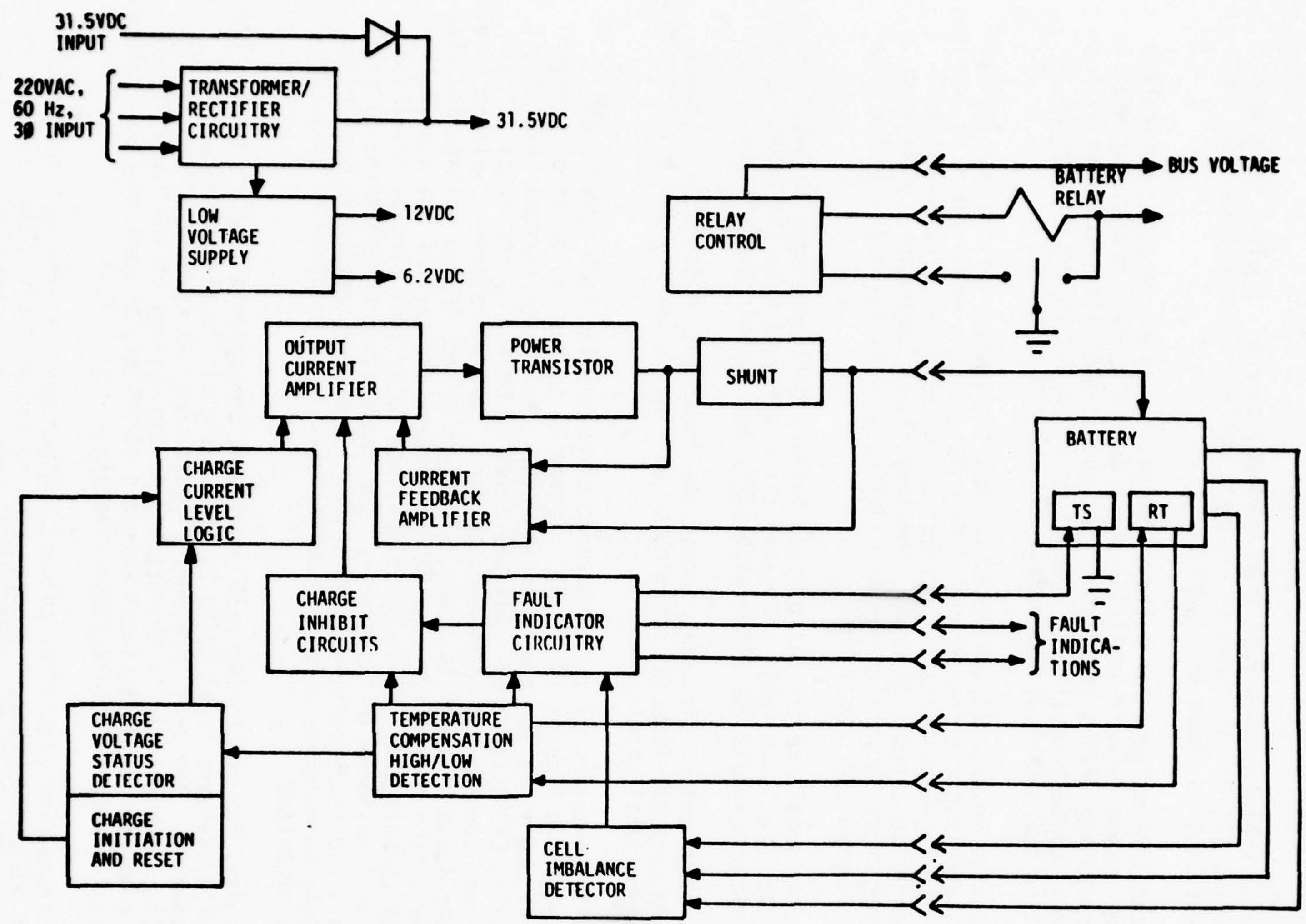


FIGURE 8. AC INPUT BIU BLOCK DIAGRAM.

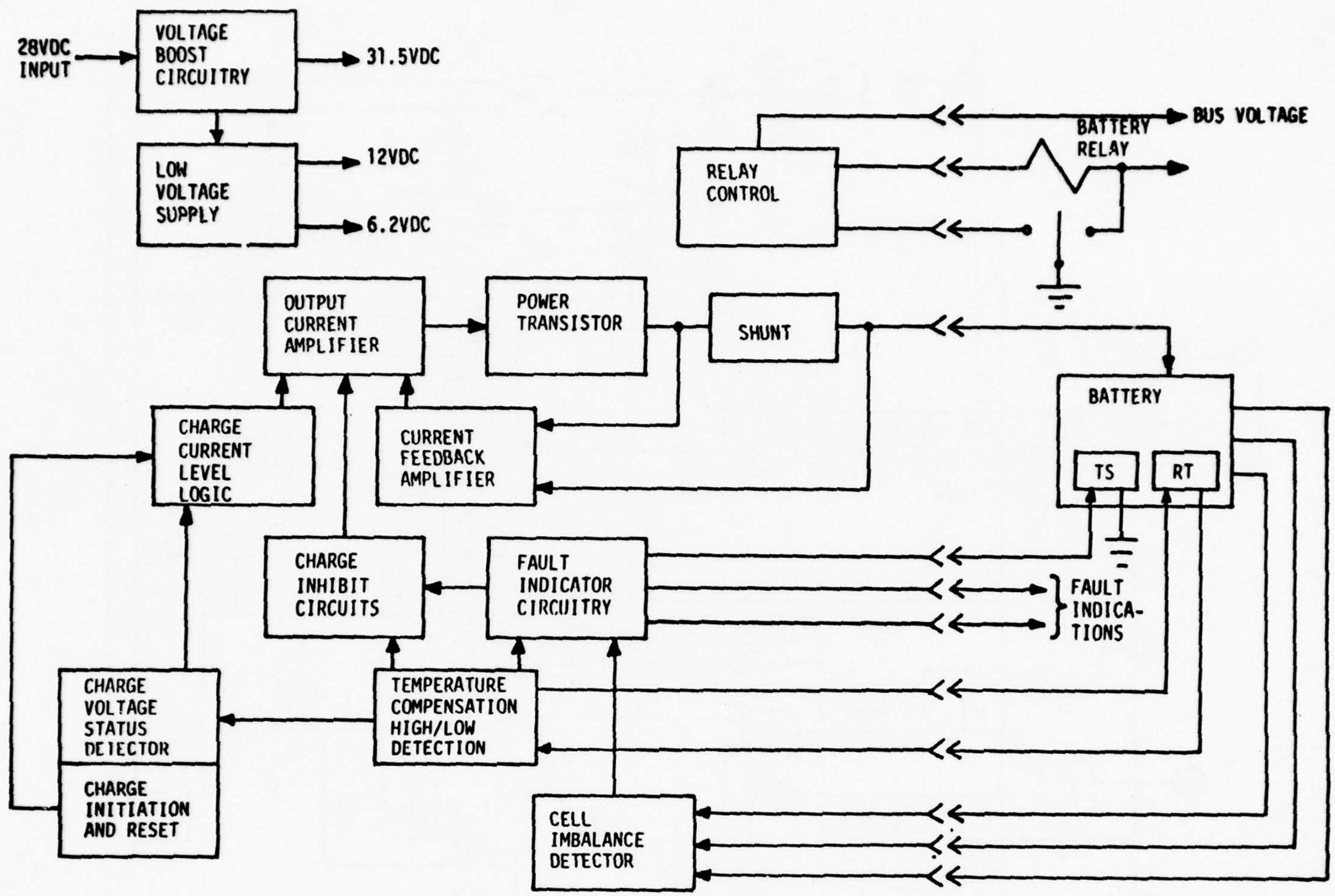


FIGURE 9. DC INPUT BIU BLOCK DIAGRAM.

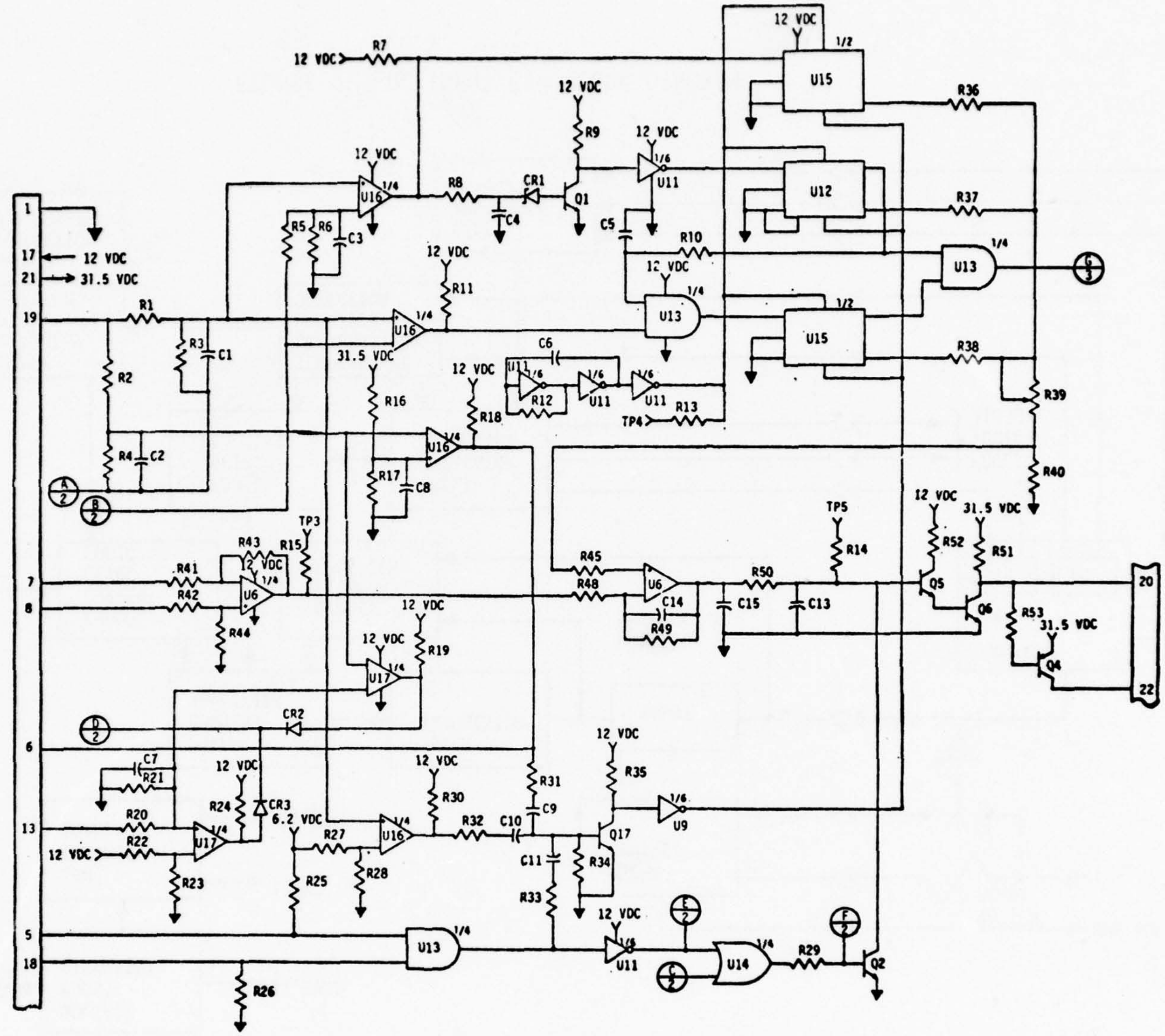


FIGURE 10. AC INPUT BIU CIRCUIT SCHEMATIC (SHEET 1 OF 3).

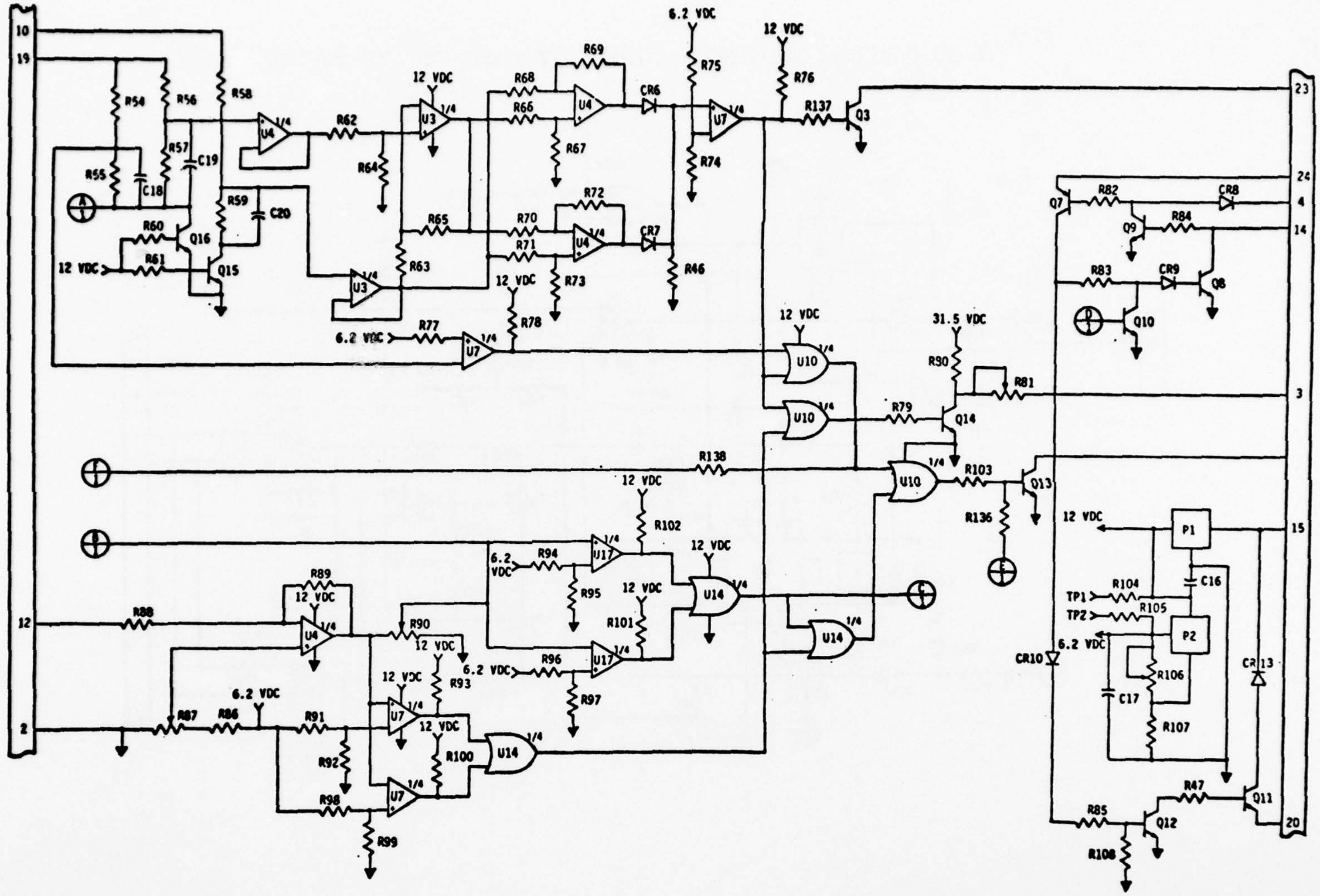


FIGURE 10. AC INPUT BIU CIRCUIT SCHEMATIC (SHEET 2 OF 3).

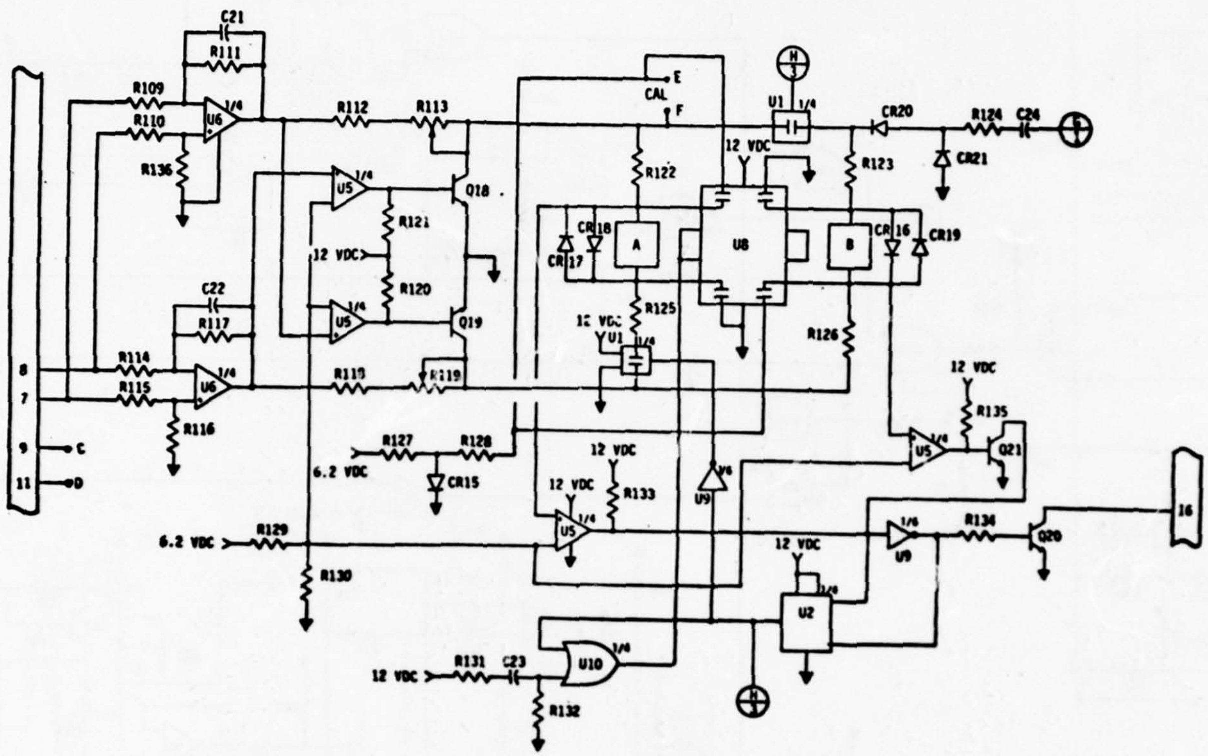


FIGURE 10. AC INPUT BIU CIBCUIT SCHEMATIC (SHEET 3 OF 3).

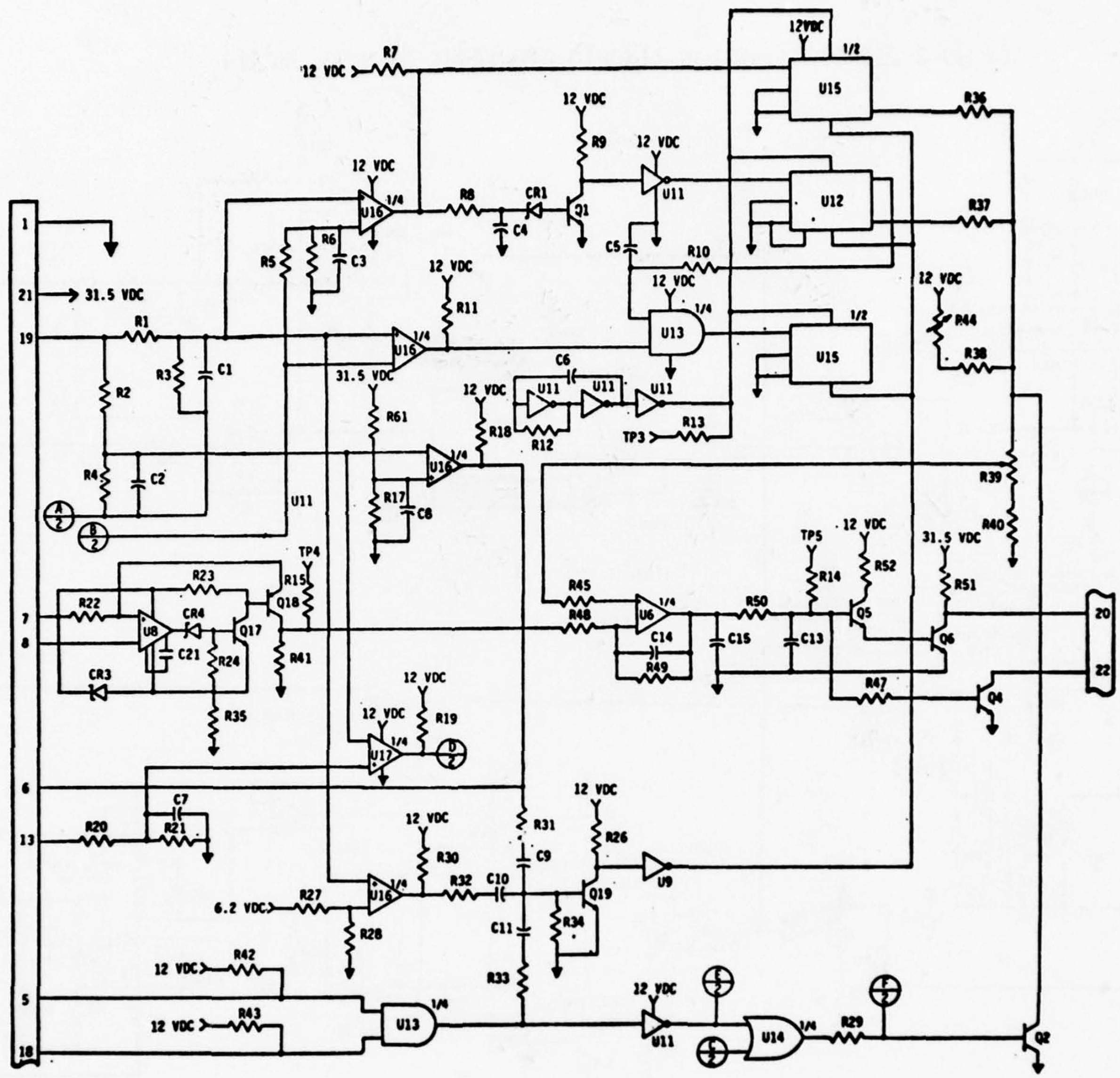


FIGURE 11. DC INPUT BIU CIRCUIT SCHEMATIC (SHEET 1 OF 2).

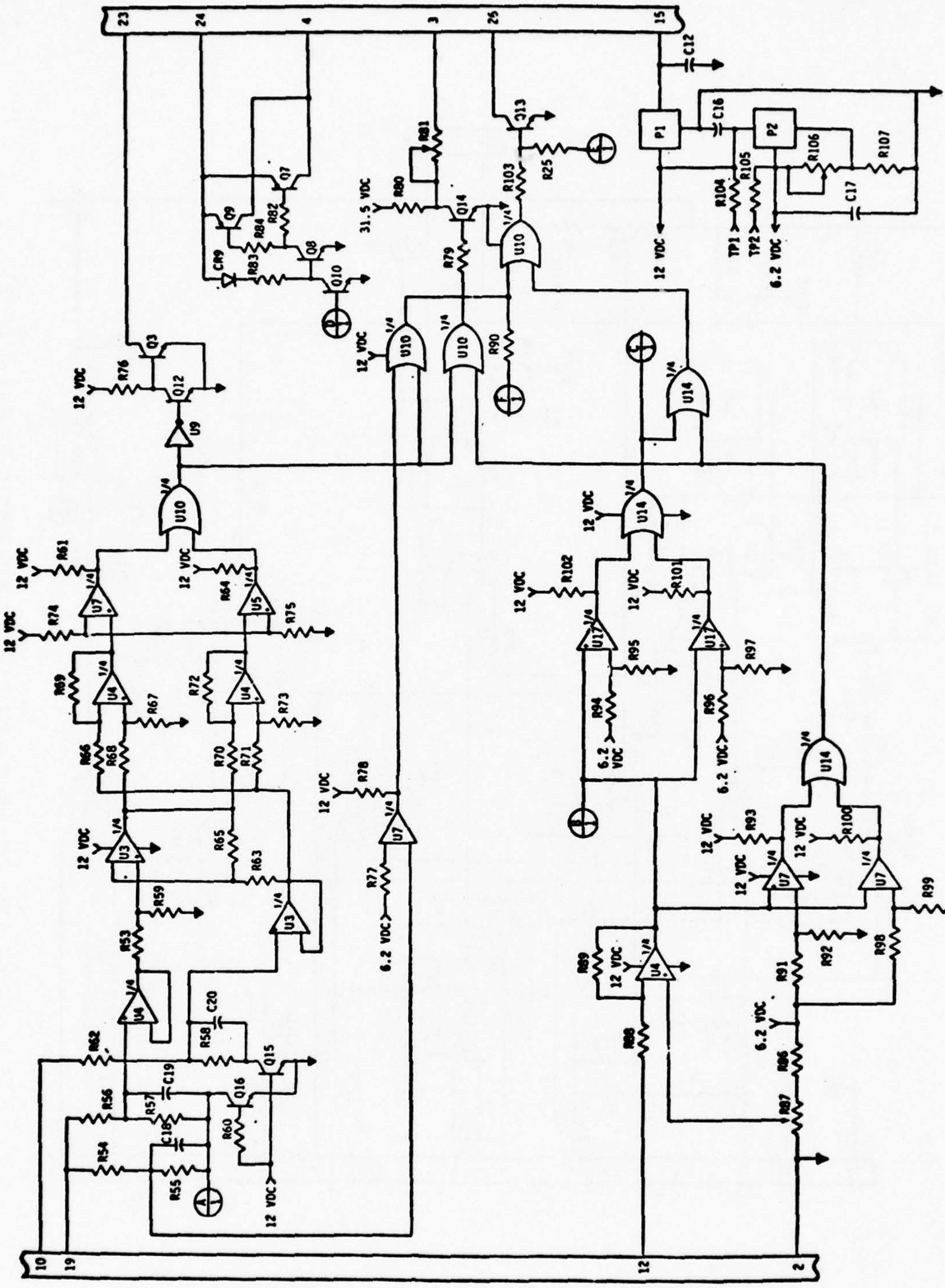


FIGURE 11. DC INPUT BIU CIRCUIT SCHEMATIC (SHEET 2 OF 2).

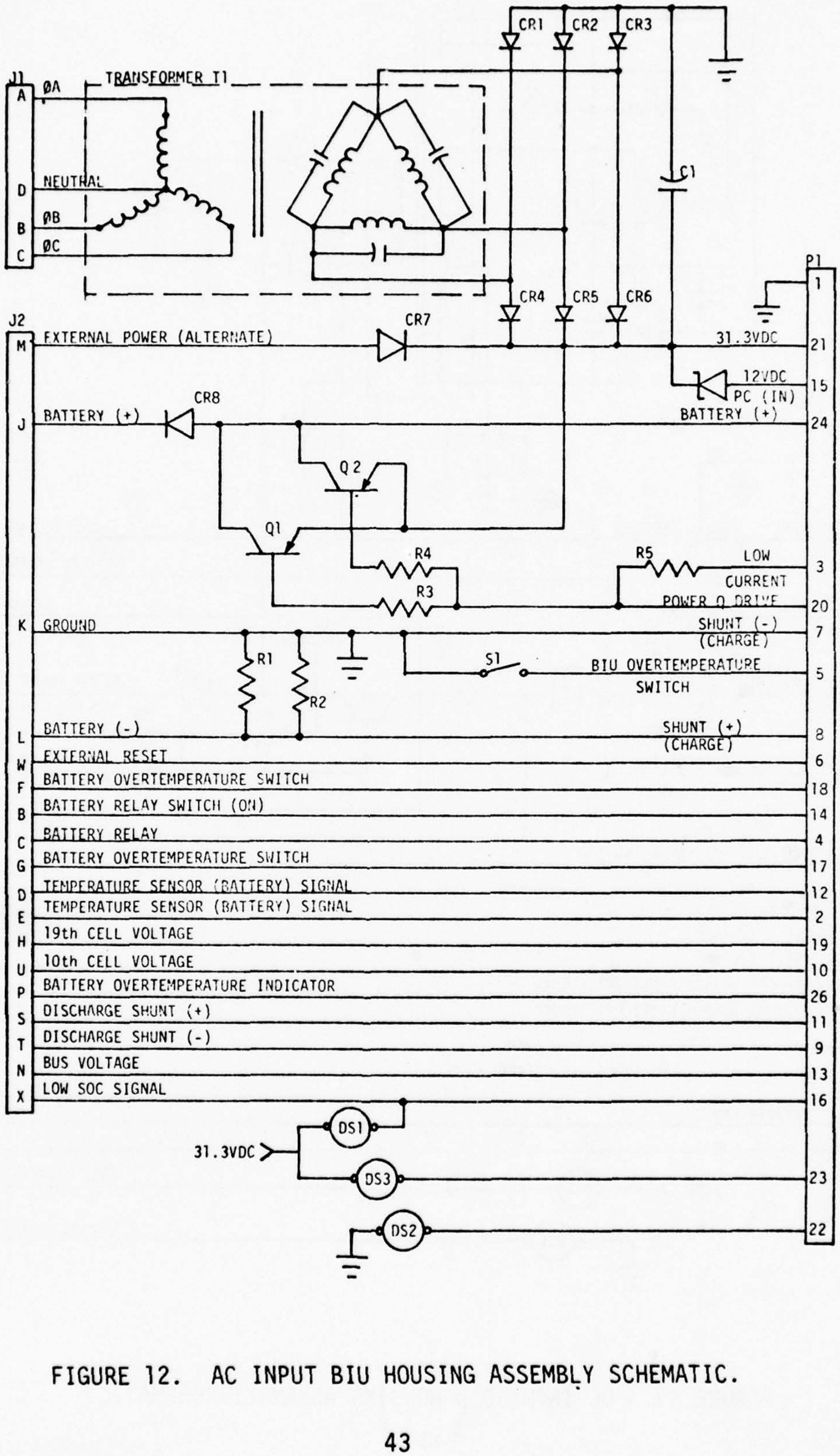


FIGURE 12. AC INPUT BIU HOUSING ASSEMBLY SCHEMATIC.

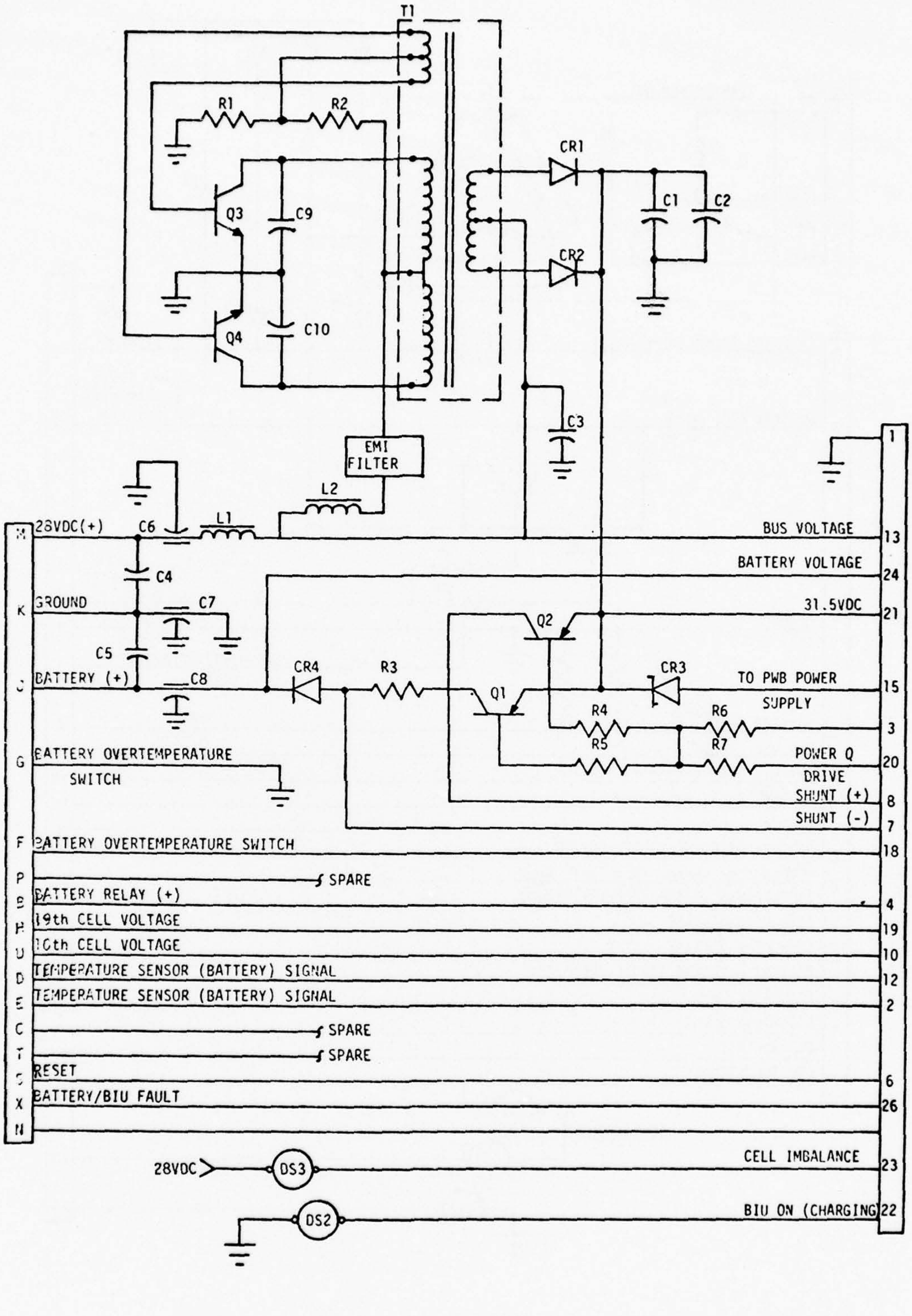


FIGURE 13. DC INPUT BIU HOUSING ASSEMBLY SCHEMATIC.

Mechanical Design Description

The outline dimension of the class III BIU is shown in Figure 14 along with the mounting provisions. Figure 15 is similar, but is for the class II BIU.

The housing for both BIUs is of aluminum sheet metal construction. It contains the indicators for fault annunciation, connectors, and a hinged gasket-sealed cover.

Low power electronic components are mounted on a printed wiring board (PWB). The PWB is mounted on the inside of the hinged cover of the housing assembly. Test points are provided for servicing and fault isolation.

Components that dissipate significant amounts of power are mounted on the sides of the housing assembly, which is convection cooled. Finned-type heat radiators are used to allow adequate convection cooling. Total heat dissipation is less than 100 watts.

FABRICATION

Three prototype BIU assemblies of each type were fabricated in the Chrysler engineering prototype shop. Minor modifications and design improvements were made to the BIU during the test phase of the program. Photographs of the final AC input BIU assembly are shown in Figures 16 and 17.

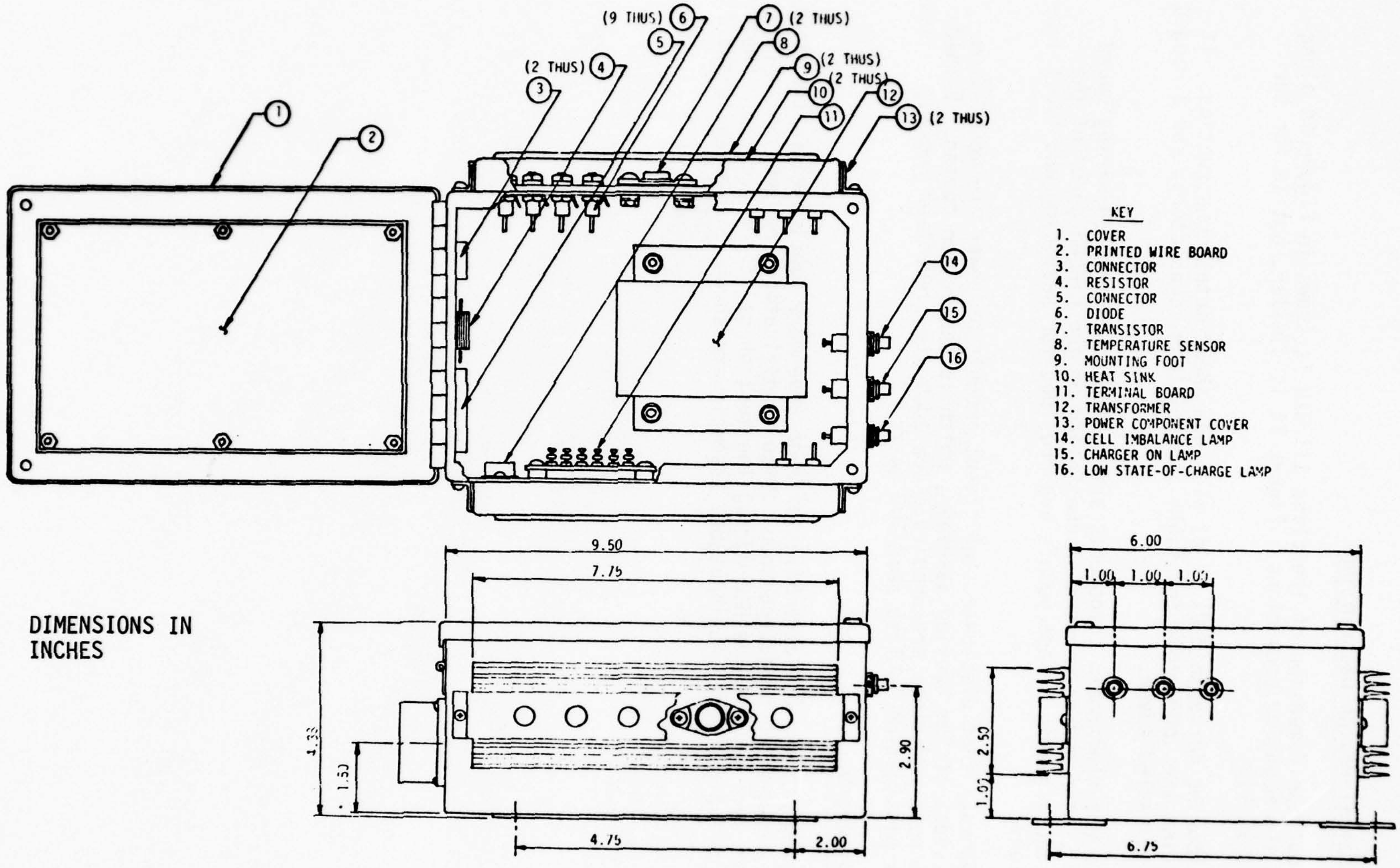


FIGURE 14. AC INPUT BIU COMPONENT LOCATION AND DIMENSIONS.

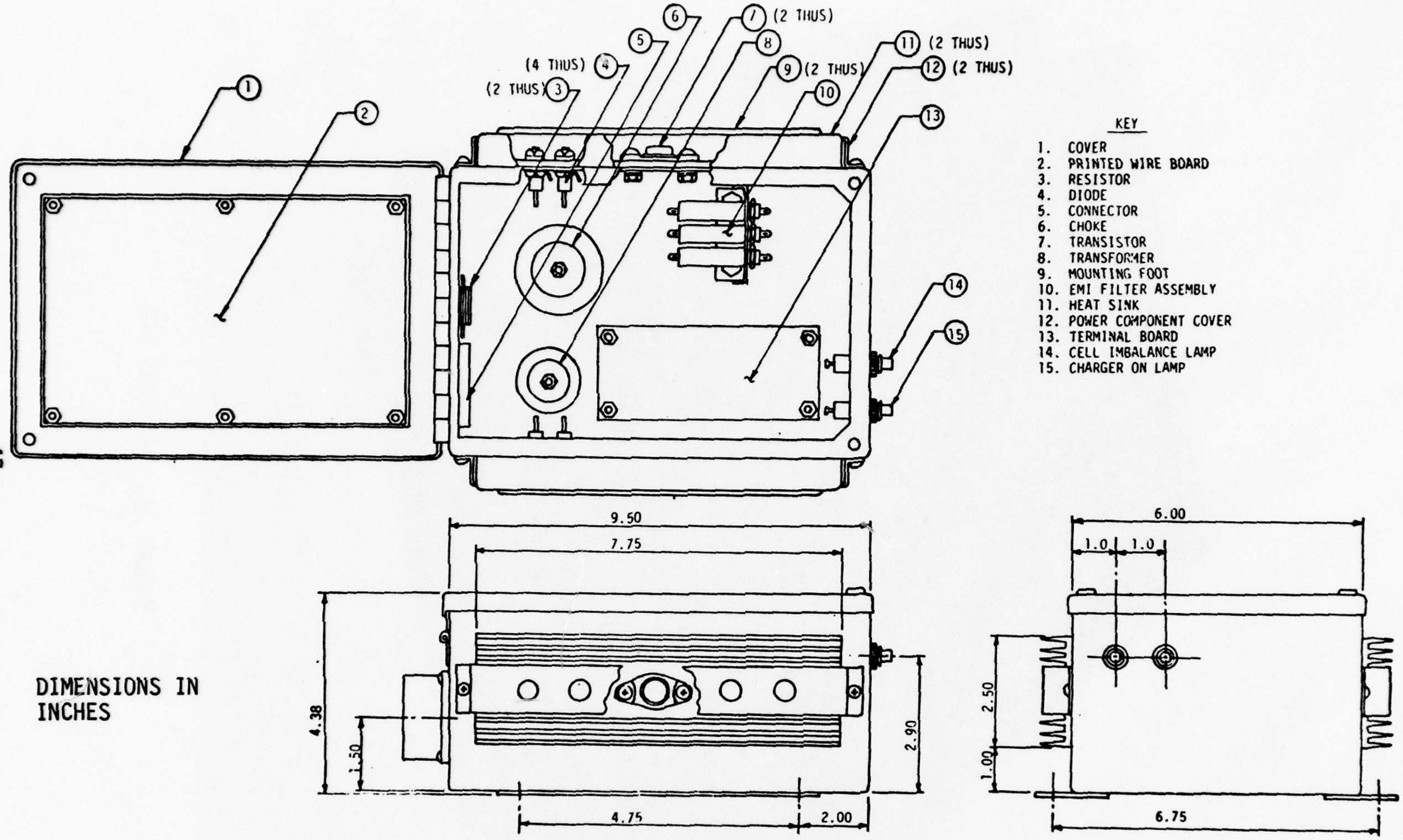


FIGURE 15. DC INPUT BIU COMPONENT LOCATION AND DIMENSIONS.

FIGURE 16. AC INPUT BIU.

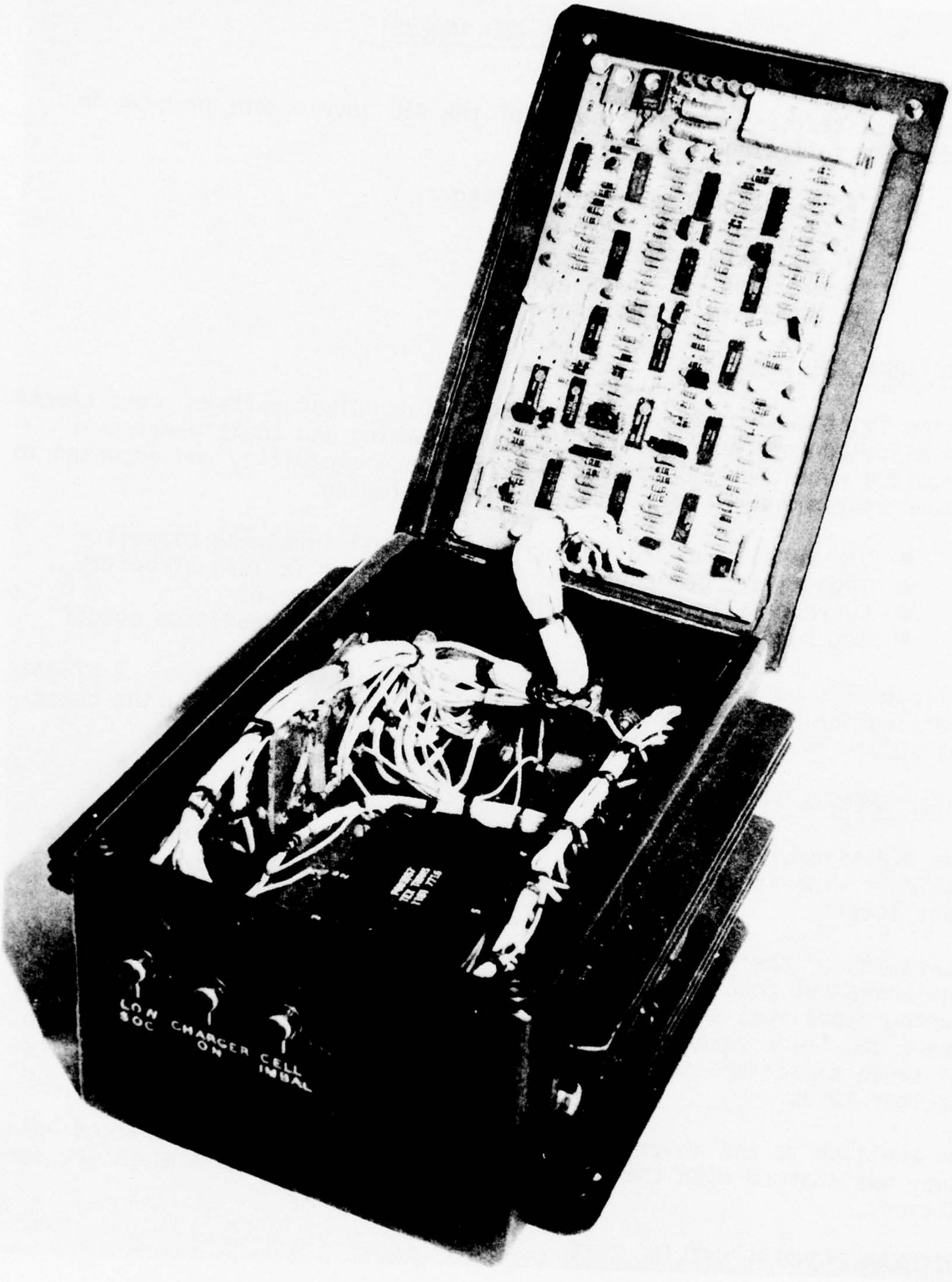


FIGURE 17. AC INPUT BIU WITH THE COVER OPEN.

TESTING AND ANALYSIS

The Task V test and analysis phase of the BIU development program included the following:

- Functional checkout testing
- Environmental testing
- Discharge/charge testing
- Testing of add-on BIUs
- Analysis of test data

FUNCTIONAL CHECKOUT TEST

During functional checkout, all power supply output voltages were checked and adjusted to proper levels. All programming and logic electronic circuitry were checked for proper performance capability and adjusted to proper operational levels including the following:

- BIU reset
- Temperature compensation
- Current level switching logic
- SOC cutoff level
- Cell imbalance circuitry
- Sensor failure circuitry
- Safe current
- Abnormal condition cutoff

All circuits performed their basic functions during checkout. A slight modification was made to the reset and SOC logic circuits during checkout to achieve reliable operation.

ENVIRONMENTAL TESTING

One BIU assembly was subjected to the environmental tests outlined in Table 7. The stress level represents typical aircraft environmental test levels.

Operation of the BIU met specification requirements under all of these environmental conditions with no degradation in performance. However, during vibration, two ripple filter capacitor leads broke at the points where the leads entered the case. Epoxy cement was added beneath each of these capacitors so that they were not supported entirely by the capacitor leads.

In addition to the above temperature test, a completely discharged battery was charged with the BIU under the 140°F and -40°F temperature conditions.

DISCHARGE/CHARGE CYCLING TEST

One of the most important aspects of the program was the discharge/charge

TABLE 7. ENVIRONMENTAL TESTS.

Environment	Stress Level
Vibration	Procedure, Curve Z (Part 1) Method 514.1 per MIL-STD-810B
Shock	Procedures I and III, Method 516, MIL-STD-810B, pulses per Figure 516.1-2
High Temperature (Operating)	140°F
Low Temperature (Operating)	-40°F
Humidity	Method 507, MIL-STD-810B(4) Procedure IV

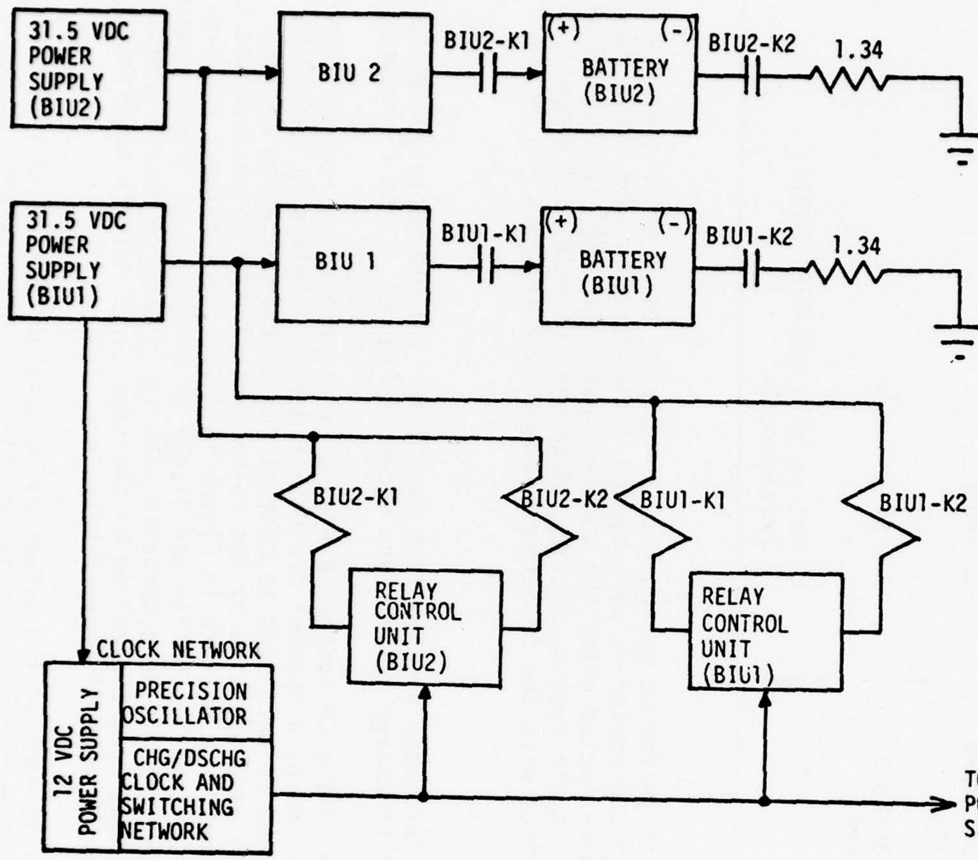
cycling tests performed during Task V. During these tests, two new 19-cell, 11AH NICAD batteries were cycled using the BIU. Two other identical batteries were cycled using the constant potential (CP) charge method. The parallel cycle testing provided data that allow direct comparison of BIU performance with the CP method used on Army aircraft now in the field.

Test Setups

The discharge/charge cycling test setups for the BIU prototype systems and for the CP charge systems are shown in Figures 18 and 19 respectively.

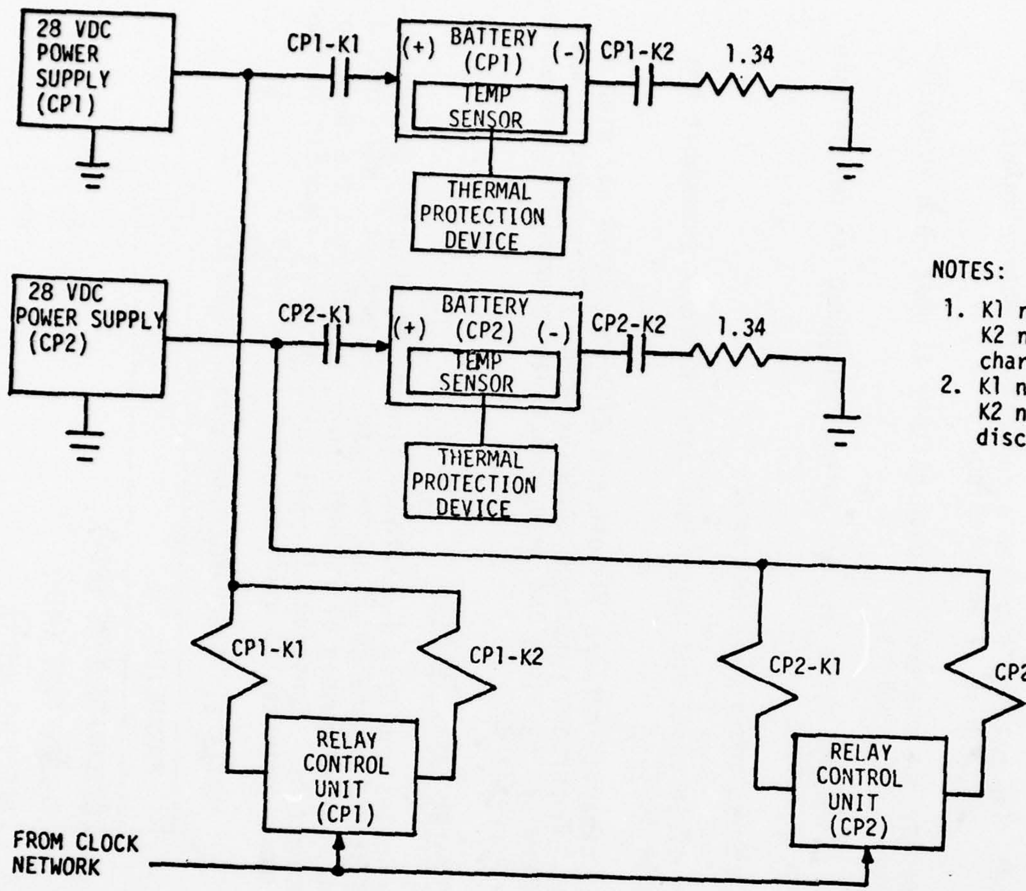
The battery in the CP system in Figure 19 was protected against thermal runaway hazards by a thermal protection device. Relays K1 and K2 in Figures 18 and 19 were used to control the discharge/charge cycles. These relays were operated by the relay control unit which received signals from the clock network in Figure 18. The clock network was programmed to control the charge and discharge times and to provide automatic switching signals in accordance with the discharge/charge profile. All four setups were controlled by the same clock network to eliminate inaccuracies between discharge/charge profiles.

The battery in each of the setups was discharged through a 1.34 ohm $\pm$ 1 percent fixed resistor during the discharge portion of each cycle.



NOTES:
1. K1 normally closed and K2 normally open during charge.
2. K1 normally open and K2 normally closed during discharge.

FIGURE 18. CYCLE TESTING SETUP FOR THE BIU SYSTEMS.



NOTES:

1. K1 normally closed and K2 normally open during charge.
2. K1 normally open and K2 normally closed during discharge.

FIGURE 19. CYCLE TESTING SETUP FOR THE CONSTANT POTENTIAL SYSTEMS.

Test Conditions

The cycle tests were conducted in a laboratory environment at a nominal temperature of 25^{o}C using the following procedures:

- Both the BIU and CP systems were automatically cycled.
- If the voltage of any battery dropped below 19.0 VDC during discharge, the battery was removed and reconditioned.

  Note: The battery retained a capacity of approximately 20 percent at reconditioning.
- Capacity was checked for each battery as near each 50-cycle interval as practical.
- The discharge cycle was monitored throughout the period once each 24 hours.
- Water was added once each week.
- The cycle count and water loss were recorded throughout the cycle tests.
- The capacity between 19-volt and 28.2-volt level was used as the 100-percent reference capacity level. This capacity was determined by using the reference capacity measuring procedure in Appendix B.

Discharge/Charge Cycle Tests

Initial cycle testing used a discharge time of 12 minutes, corresponding to a depth of discharge of approximately 50 percent. With this discharge time, the frequency of reconditioning would limit the number of cycles during test. Consequently, all batteries were reconditioned and the cycle tests reinitiated using the profile in Table 8.

TABLE 8. DISCHARGE/CHARGE CYCLE PROFILE.

PARAMETER	VALUE
DISCHARGE TIME (MIN)	7
CHARGE TIME (MIN)	42
OFF TIME (MIN)	42
AVG. DISCHARGE CURRENT (AMPS)	16.8
DEPTH OF DISCHARGE (%)	20

During the cycle tests, each battery was completely discharged to 19 volts at each 50-cycle interval to measure capacity remaining in the battery. The capacity-versus-cycle data to the time reconditioning was required is shown in Figure 20. The curves show the decrease in battery capacity as the number of cycles increases. A change in slope occurs at the points where capacity was measured because the full capacity removed from the battery during the capacity check was not returned to the battery when charged.

The water loss during the initial test cycling results is shown in Table 9.

TABLE 9. INITIAL CYCLE TESTING WATER LOSS.

BATTERY	WATER LOSS (ML)	DISCHARGE/CHARGE CYCLES	REMARKS
CP #1	200	125	Initial cycle tests-capacity measured @ 50-cycle intervals
CP #2	260	125	
BIU #1	114	127	
BIU #2	170	149	

The batteries were then reconditioned and cycle tested without measuring capacity at 50-cycle intervals. The results of this cycle testing are given in Table 10.

TABLE 10. WATER LOSS VERSUS CYCLES TO RECONDITIONING.

BATTERY	WATER LOSS (ML)	DISCHARGE/CHARGE CYCLES	REMARKS
CP #1	190	172	Cycle tests w/o measuring capacity at intervals between reconditioning
CP #2	195	172	
BIU #1	123	175	
BIU #2	179	195	

<u>Water Loss/Capacity Optimization</u>

The data in Table 10 clearly shows the BIU operation to be below the optimum water-loss-versus-capacity level. Since the water loss is a very

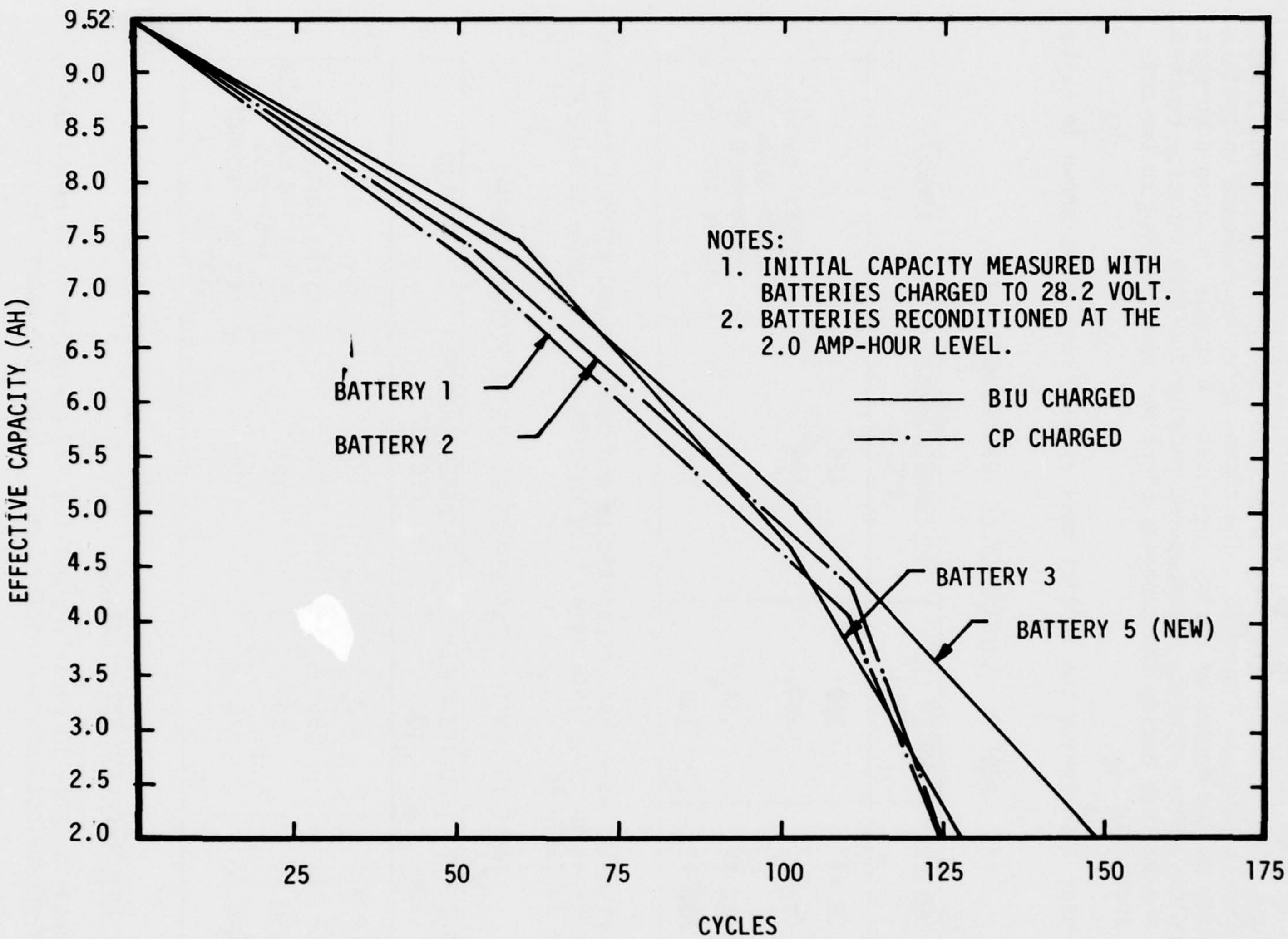


FIGURE 20. EFFECTIVE CAPACITY AS A FUNCTION OF CYCLE.

small portion of the 304 ml in the battery, the charge input to the battery can be increased without resulting in excessive water loss. The increased charge results in more capacity into the battery, providing for a greater number of cycles of operation before reconditioning is required. A series of water loss/capacity optimization tests were conducted to determine the optimum BIU current/voltage profile to provide for the increased battery charge.

The first optimization cycle tests were performed with the BIU's in the following configuration:

- One BIU was operated with the cutoff voltage increased to 29.2 VDC and the third constant current level set to 1 ampere.
- One BIU was operated using the regular 28.2 VDC cutoff voltage and the third constant current level "ON" 100 percent of the time at an amplitude of 1 ampere.

The results of these tests are shown in Table 11.

TABLE 11. OPTIMUM WATER LOSS/CAPACITY RESULTS.

BIU RPOFILE	WATER LOSS (ML)	CYCLES	REMARKS
29.2-volt level	154	180	Recondition required
1-amp topping charge current	1344	700	Battery capacity at 40.8% level

The results clearly show that the third-step topping charge current approach offered the greater advantage in achieving optimum water loss versus cycles. The 1-ampere current level is too high, as indicated by the excessive water loss. It was determined from an analysis of the general water loss characteristics of NICAD batteries and the cycle test data that the current level should be approxiamtely 0.5 ampere or less.

Verification Cycle Tests

The second series of cycle tests was conducted with the BIU third-step topping charge current set to 0.5 ampere. Two batteries were cycled; one was the battery having the greatest water loss during previous testing. The results of the cycle tests are presented in Table 12.

TABLE 12. WATER LOSS/CYCLE VERIFICATION DATA.

BATTERY*	WATER LOSS	CYCLES	CAPACITY END OF CYCLE TEST
#1	308	408	36.3%
#2	528	469	42.1%

* BIU @ 0.5 ampere third-step topping charge

SUPPLEMENTAL BIUs

During the later stage of the development program the contract was modified to include fabrication of three additional BIU assemblies and to add additional environmental tests. These BIUs were of the same configuration as the original BIUs except for input power form. The SOC circuitry was omitted from these BIUs.

The supplemental BIUs were designed to operate with an input voltage of 26.5 $\pm$ 2.0 VDC. The BIU boosts this voltage to 31.5 $\pm$ .2 VDC for a temperature-compensated charge profile.

The supplemental prototype BIUs were checked out and performance tested in accordance with the same procedure as the initial batch of prototypes. These units were subjected to further testing as follows:

- One BIU was subjected to 100 hours of cycle testing at maximum load. During the first 50 hours, the load was alternately switched off and on for 5-second periods. During the last 50 hours, the test was repeated with the input on and the load being switched.
- The second BIU was subjected to all the environmental tests in Table 13 except EMI (electromagnetic interference).
- The third BIU was subjected to the EMI test defined in Table 13.

The cycle tests were completed without any BIU failures or degradation of performance.

The second BIU met specification requirements under the environmental conditions to which it was subjected.

TABLE 13. ADDITIONAL ENVIRONMENTAL TEST REQUIREMENTS.

Environment	Stress Level
Temperature/Altitude	MIL-STD-810B, Method 504 Procedure I, Class 1B Equipment
Explosive Atmosphere	MIL-STD-810B, Method 511 Procedure I
Electromagnetic Interference	Test Method MIL-STD-462 to requirements of MIL-STD-461 Change Notice 4, Category IC Airborne Equipment -- Except low frequency for CE01 was 2 kHz

During the EMI testing, the BIU was subject to the following tests as defined by MIL-STD-461, Change Notice 4:

- CE01
- CE04
- CS01
- CS02
- CS06
- RE02
- RS02
- RS03

The BIU did not meet the requirements of MIL-STD-461 during the initial EMI test. The unit was modified to include EMI and line filtering and was retested.

During the retest the unit met the entire CS01, CS02, CS06, and RS02 requirements. The performance of the BIU was slightly above the limits specified in MIL-STD-461 at certain frequency points during the other EMI test. These out-of-tolerance conditions are summarized in Table 14.

Any production BIUs that are required to meet the full extent of the above MIL-STD-461 requirements will require additional EMI filtering. This is readily feasible, as indicated by the tremendous EMI data improvement when the EMI and line filters were installed in the prototype BIU.

TABLE 14. EMI OUT-OF-TOLERANCE CONDITIONS.

TEST	MEASUREMENT POINT	RESULT
CE01	+28 VDC Line +28 VDC Return	1 point + 3dB @ 45.9 kHz 1 point + 15dB @ 48.8 kHz
CE04 Wide Band	+28 VDC Line +28 VDC Return	1 point + 2dB @ 0.16 mHz 1 point + 1dB @2.0 mHz
CE04 Narrow Band	+28 VDC Line +28 VDC Return	4 dB @ 0.11 mHz & 8dB @ 0.21 mHz 6 dB @ 0.08 mHz, 11dB @ 0.11 mHz & 13 dB @ 0.16 mHz
RE02 Narrow Band		6 frequency points 7,7,6,6, 5, & 2 dB above limit
RS03 Below 30 mHz		BIU performs satisfactorily
Above 30 mHz		BIU charge current increases to a current limited to 14.5 amperes when field is increased to 10 V/meter.

TEST DATA ANALYSIS

Performance Data

The BIU satisfactorily met the performance requirements of the general BIU specification prepared during Task II of the program. However, the following design improvements should be accomplished in any production-type BIU:

- SOC Circuit (if required) - Even though the circuit functions satisfactorily, it is quite complex and should be simplified.

- EMI Filters - The EMI filters should be optimized or additional filtering added if the full extent of MIL-STD-461 is required.

The high reliability of the BIU was demonstrated by operating over 3800 cycles during the test program without an operational failure.

Cycle Test Data

Table 15 allows a direct parallel comparison of the BIU performance data against the CP system presently used in Army aircraft under the same operational conditions.

TABLE 15. CP AND FINAL BIU CYCLING TEST DATA.

SYSTEM	CYCLES	WATER LOSS (ML)	WATER LOSS (ML/CYCLE)	CAPACITY IN BATTERY
CP #1	172	190	1.105	Recondition
CP #2	172	195	1.134	Recondition
BIU #1	408	308	0.755	42.1%
BIU #2	469	528	1.126	36.3%

From the data in Table 15 the average water losses for the CO and BIU systems are 1.119 ml/cycle respectively. This represents an improvement in average water loss of approximately 15.9 percent.

The improvement in battery capacity retention represents one of the greatest advantages in using the BIU to provide for improved maintenance and maximum utilization of NICAD batteries. The batteries on the CP system required reconditioning after 172 cycles, whereas the BIU batteries were cycled well over 400 cycles without approaching the reconditioning capacity level. The data represents an improvement of 250 percent in operational cycles before battery reconditioning is required.

The performance data clearly indicate that use of the BIU will allow longer periods of battery usage without requiring reconditioning as well as improve battery capacity retention per cycle.

In addition to the improved maintenance and battery utilization, the BIU provides the following additional advantages:

- Protection against thermal runaway
- Low cost and high reliability
- Import battery status information such as cell imbalance, BIU and battery sensor faults
- Longer lasting life by elimination of hazards which cause battery cell failures

Environmental Test Data

BIU operation was satisfactory when subjected to the aircraft environ-

ments and stress levels in Tables 7 and 13 with the exception of a portion of the EMI tests. From the results of the tests, it is apparent that minor redesign of the input filter will result in a unit which will meet the EMI requirements.

CONCLUDING REMARKS

The analytical portions of the program (Tasks I and II) were concerned with evaluation of the various charge concepts that could be used for the BIU and detailed analysis to determine the relative merits of each in comparison with the presently used constant potential charge method. The results of this analysis clearly showed that improved battery life, reduced battery maintenance, and elimination of potential battery hazards would result from using any of the charger approaches considered. Specifically, the analysis showed that scheduled maintenance could be reduced from present levels. Further, the frequency of unscheduled maintenance, a major cost factor, could be drastically reduced. Of the charger approaches considered, the multilevel, constant current approach proved to be optimum in terms of performance and was selected for use in subsequent tasks for this reason.

The design and fabrication tasks (Tasks III, IV, and VI) demonstrated that a unit would be designed to implement the selected charger approach using state-of-the-art techniques. Further, the design was of a simple enough nature that the resulting BIU would have acceptable reliability and could be easily maintained. The design is flexible enough that it can be adapted to applications for other than the 11 ampere-hour battery used as the baseline. The design of the BIU package is such that weight and volume limitations for aircraft equipment can be met.

The results of the test program (Task V) verified the analytical predictions. Over 3,800 cycles without operational failure of the BIU or battery demonstrated the high reliability of the unit. The cycle testing also demonstrated that the unscheduled removals will be drastically reduced when the BIU is used in an operational environment.

When used operationally, a NICAD battery must be removed from the aircraft on a periodic basis to recondition or to add water. The period of time between such scheduled maintenance can be greatly increased when the BIU is used. The water loss/capacity loss tests defined a charge rate for the third step in the charge sequence that effected a 15-percent reduction in water loss and a 250-percent improvement in capacity retention per cycle when compared to the constant potential charge method. It should be noted that at the end of 400 cycles the batteries charged with the BIU retained a capacity of almost 40 percent.

The results of the environmental tests showed the BIU as designed will withstand use in an aircraft environment. Initial EMI testing indicated the need for filtering to meet MIL-STD-461. Though the final EMI testing did not meet all requirements of this MIL-STD, the magnitude of the reduction in EMI with the addition of filters strongly indicates that with additional optimization of the filter design all EMI requirements can be met.

The results of the program met the original objectives. There are, however, areas where additional work should be done in order to optimize the design for general Army aircraft applications. The major areas for such effort are:

- The package design should be optimized to assure minimum weight and volume consistant with good manufacturing practice and environmental survivability.
- Further optimization of the third step in the charge sequence could result in a better balance between water retention and charge retention. In the ideal situation the need to add water and the need to recondition should occur at the same point in the cycle life.
- The EMI filter design should be optimized to assure full compliance with MIL-STD-461.
- Though the SOC circuits function satisfactorily, these circuits are quite complex and should be simplified if, in fact, they are required.

APPENDIX A

PROTOTYPE BIU FOR NICAD AIRCRAFT BATTERIES, GENERAL SPECIFICATION

1.0 SCOPE.

This specification covers the general design and performance requirements for the Battery Interface Unit (BIU) to be used for onboard charging of nickel-cadmium batteries for Army aircraft. The unit is referred to herein as the BIU.

2.0 APPLICABLE DOCUMENTS.

The following documents form a part of this specification to the extent specified herein. In the case of conflict between document and this specification, the specification shall apply.

MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-810B	Environmental Test Methods for Military Equipment

3.0 REQUIREMENTS.

3.1 BIU DEFINITIONS. The BIU converts the standard aircraft input voltage into the temperature-compensated DC level to charge an 11 ampere-hour, 19-cell, nickel-cadmium (NICAD) battery in accordance with the requirements of this specification. The BIUs specified herein will be of three classes in accordance with the following definitions:

Class I - On-line charger - Operation from the DC bus in the aircraft with the upper battery charge voltage limited by the magnitude of the bus voltage.

Class II - Off-line charger - Operation from the DC bus in the aircraft with a boost circuit to provide a maximum battery charge voltage of 31.5 $\pm$ 0.2 VDC.

Class III - Off-line charger - Operation from the standard 400-Hz, 3-phase voltage in the aircraft to provide a maximum battery charge voltage of 31.5 $\pm$ 0.2 VDC.

The general requirements of this specification apply to all three classes of BIUs unless otherwise noted.

3.2 FUNCTIONAL REQUIREMENTS. The BIU shall perform to the requirements of this specification when furnished airborne or ground input power as specified herein.

3.2.1 BIU Operation. The BIU shall be capable of charging a completely discharged battery (0.0 volt) in accordance with the requirements herein.

3.2.2 Maximum Charge Time. The maximum charge time at ambient temperature (25°C) shall be as shown in Table A-1.

TABLE A-1. MAXIMUM CHARGE TIME.

Charge Condition	Charge Time (hr)
From 0.0 V/Cell to 75-percent SOC	1.0
From 0.0 V/Cell to 100-percent SOC	2.0
From 50-percent SOC to 100-percent SOC	1.0

3.2.3 Charge Current. The charge current of the BIU shall be in accordance with the voltage/current profile shown in Figure A-1. The level of the charge current shall be the indicated level with a tolerance of plus 3 percent and minus 6 percent of nominal.

3.2.4 Charging Modes. The BIU shall provide for the following three operational current modes in accordance with the voltage/current profile in Figure A-1:

Mode A - Constant current equal to 1C rate until the battery voltage approaches the predetermined voltage level.

Mode B - Constant current equal to 0.4C rate until the battery voltage approaches the predetermined voltage level.

Mode C - Continuous constant current equal to 0.05C rate.

3.2.5 Charge Mode Determination. The initial operation of the charger is always in Mode A. The charger switches to Mode B and then to Mode C as the battery terminal voltage approaches the predetermined voltage for properly charging the battery. The predetermined voltage shall be the temperature-compensated voltage shown in Figure A-2. The Class I type

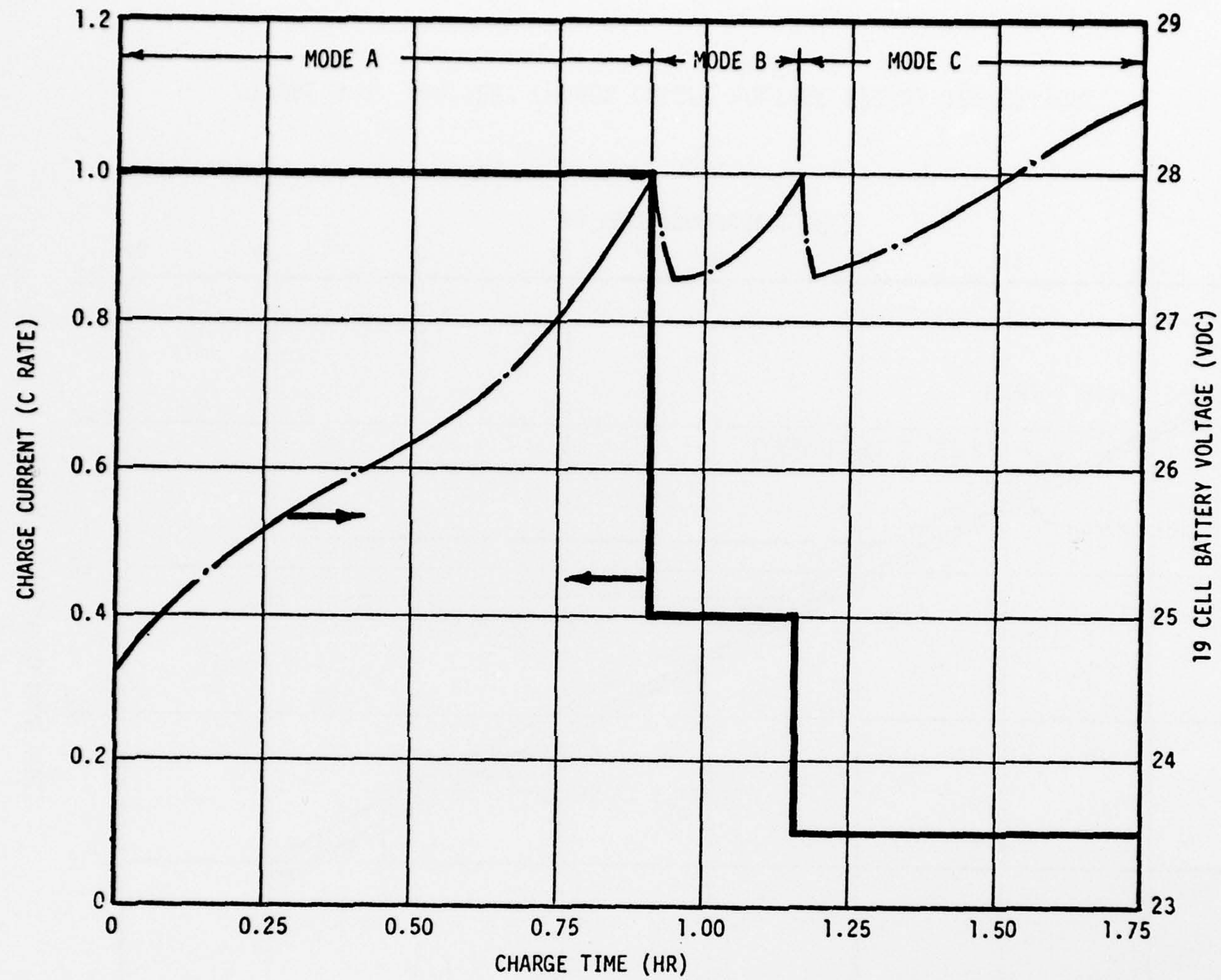


FIGURE A-1. CHARGE CURRENT/VOLTAGE PROFILE.

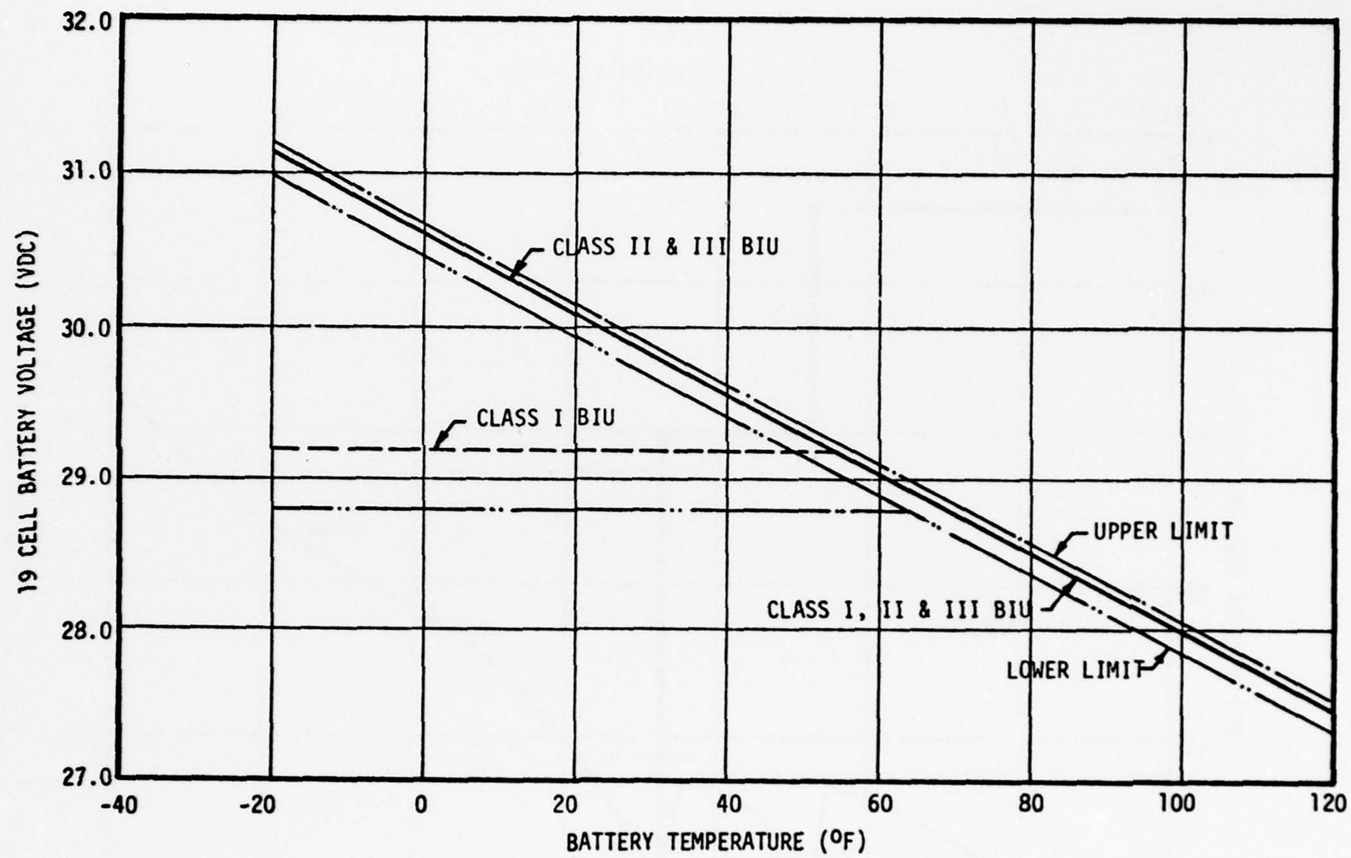


FIGURE A-2. BATTERY CHARGE CUTOFF VOLTAGE VERSUS TEMPERATURE.

BIU will be limited to the bus voltage minus 0.4 VDC at low temperature condition (indicated by dashed line in Figure A-2).

If the input voltage to the BIU causes the charge voltage to fall below the value shown in Figure A-2, the BIU shall operate in a constant voltage mode. The current shall be limited to the 1C rate during this constant voltage mode. Normal charging shall resume when the low voltage condition is corrected.

3.2.6 Charge Initiation. The BIU shall initiate battery charge within 1.5 seconds under the following conditions:

- Proper power is applied to the charger.
- Unloaded battery condition following a loaded condition.
- Overtemperature either in the battery or BIU is eliminated.
- Improper power condition is corrected.

3.2.7 Cutoff Signals. The BIU shall generate signals that will terminate charging under any of the following conditions:

- Battery overtemperature (130 ± 5°F).
- BIU overtemperature.
- Load placed on battery.
- Incorrect power condition.
- Excessive cell imbalance condition.
- Low battery temperature (-30 ± 5°F).

3.2.8 Reduced Operation. The BIU shall operate at a safe, reduced current level in case of an open or short circuit temperature sensor failure.

3.3 BIU - MONITORING FUNCTIONS. The BIU shall provide for the following monitoring and display functions:

- Battery temperature
- Battery overtemperature
- BIU overtemperature
- Cell voltage imbalance
- Battery state of charge (SOC)
- BIU charging status display
- SOC display
- Cell voltage balance display

3.3.1 Battery Temperature. Battery temperature will be monitored with a resistance-type thermal device.

3.3.2 Battery Overtemperature. Battery overtemperature signal will be derived from a fixed level thermal switch.

3.3.3 BIU Overtemperature. BIU overtemperature shall be monitored by a discrete-type thermal switch with a cutoff temperature of 185 ± 10°F.

3.3.4 Cell Voltage Imbalance. Cell voltage imbalance shall be deter-

mined by monitoring the potential at one or more points between cells. An indicator shall indicate cell imbalance when the potential difference between 10 of the battery cells and 10/9 times the potential of the other nine cells is 1.0 $\pm$ 0.1 volts. For 20-cell batteries the potential difference will be between 10 cell sections.

3.3.5 State of Charge (SOC). The SOC of the battery shall be determined by integration of the battery input and output current by using either analog or digital circuitry. A SOC indication of 100 percent will be based on a fully charged battery of a given ampere-hour rating. The SOC circuit will compensate for stand loss and charge efficiency. Charge efficiency will be adjusted for 85 percent and the stand loss for 1.2 percent per 24 hours.

> NOTE: The SOC is a measure of charge status of the battery and not the output capacity, since it does not compensate for capacity changes due to battery aging, temperature, cycling memory, etc.

3.3.5.1 SOC Readout. The BIU shall provide a meter-type SOC readout with an accuracy of plus 2.5, minus 10 percent.

3.3.5.2 Low SOC Output. The BIU shall provide a signal capable of driving a 20 milliampere lamp when the SOC is less than 40 percent (plus 10 percent minus 1.0 percent).

3.3.6 Charging Status of BIU. Logic signals shall be generated in the BIU which can be used to indicate when the BIU is charging or when it is in a cutoff or fault-type condition.

3.4 ELECTRICAL INTERFACES.

3.4.1 Input Power. Input power for the BIU shall be obtained for the BIU as follows:

- Class I BIU - Standard aircraft DC bus
- Class II BIU - Standard aircraft DC bus
- Class III BIU - Standard aircraft 400 Hz, 3-phase, AC bus

3.4.2 Battery Temperature Sensor. The linear and discrete temperature sensors shall be mounted in the same assembly with the leads from the battery brought out through a MIL-SPEC type connector. The sensor assembly will be designed to connect to an intercell terminal in the battery or to the bus bar between terminal connections (see Figures A-3 and A-4).

3.4.3 Cell Imbalance Connections. Cell imbalance connections will made on the plus side of the 10th cell and the 19th cell as counted from the minus (-) terminal of the battery.

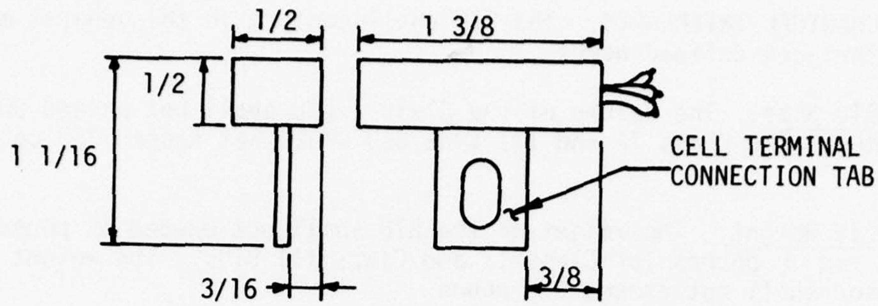


FIGURE A-3. CELL TERMINAL CONNECTED TEMPERATURE SENSOR.

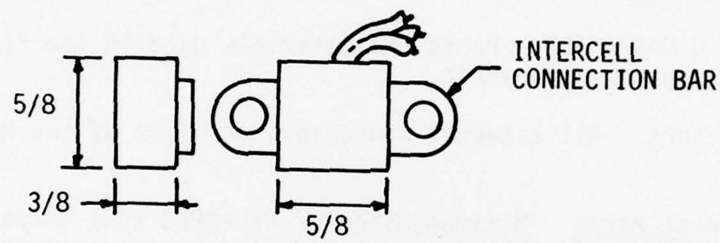


FIGURE A-4. INTERCELL BAR MOUNTED TEMPERATURE SENSOR.

3.4.4 Short Circuit. The BIU shall withstand a short circuit across the output for a minimum of 1/2 hour.

3.4.5 Open Circuit. The BIU shall not be damaged by an open circuit at the output.

3.4.6 EMI/EMC Requirement. The BIU will meet the applicable requirements of MIL-STD-461 for this class of equipment.

3.5 MECHANICAL INTERFACES. The BIU shall conform to the general mechanical interfaces defined herein.

3.5.1 BIU Size. The volume of the Class I BIU shall not exceed 300 cubic inches. The Class II and III type BIU shall not exceed 350 cubic inches.

3.5.2 BIU Weight. The weight of the BIU shall not exceed 6 pounds for Class I and 9 pounds for Class II and Class III BIUs. The weight of the sensor shall not exceed 0.2 pound.

3.5.3 Cooling. The BIU shall be designed for convection-type cooling. No forced air will be required.

3.5.4 Operational Position. The BIU shall be capable of operating in any position.

3.5.5 Adjustments. The BIU shall require no external adjustments.

3.6 PARTS AND MATERIALS. Parts and materials used in the BIU shall conform to the requirements herein.

3.6.1 Connectors. All external connectors shall be of the MIL-SPEC type.

3.6.2 Component Parts. Maximum usage of MIL-SPEC type components shall be made in the BIU. In the prototype BIU, industrial equivalent components may be substituted for MIL-SPEC parts where long lead time is a problem in meeting program schedule.

3.7 MANUFACTURING AND QUALITY REQUIREMENTS. The BIU shall conform to the manufacturing and quality requirements in paragraphs 3.7.1 through 3.7.4.

3.7.1 Maintainability. The BIU shall be designed to facilitate assembly, disassembly, location of trouble sources, and maintenance without the aid of special tools.

3.7.2 Interchangeability. Each item of the same part number manufactured in accordance with this specification shall be physically and functionally interchangeable with items bearing the same part number.

3.7.3 Workmanship. Workmanship shall be in accordance with high-grade manufacturing practices. The BIUs shall be free from dirt, sand, metal chips, machining compounds, and other foreign matter. All machined surfaces shall have a smooth finish and be free from burrs.

3.7.4 Inspection and Test. The supplier is responsible for all perform-

ance testing. He may use his own facilities or a commercial laboratory acceptable to the Government. Records of the test results shall be kept complete and available to the Government.

3.8 ENVIRONMENTAL REQUIREMENTS. The performance of the BIU shall not be impaired when subjected to the environmental conditions specified in Table A-2.

TABLE A-2. ENVIRONMENTAL TESTS.

Environment	Stress Level
Vibration	Procedure, Curve Z (Part 1) Method 514.1 per MIL-STD-810B
Shock	Procedure I and III, Method 516, MIL-STD-810B, Pulses per figure 516.1-2
High Temperature (BIU Operating)	$160^{o}F$
Low Temperature (BIU Operating)	$-40^{o}F$
Humidity	Method 507, MIL-STD-810B(4) Procedure IV
Temperature/Altitude	Method 504, MIL-STD-810B, Procedure I, Class 1B Equipment
Explosive Atmosphere	MIL-STD-810B, Method 511, Procedure I
Electromagnetic Interference	Test Method MIL-STD-462 to requirements of MIL-STD-461, Change Notice 4, Category 1C Airborne Equipment

APPENDIX B

REFERENCE CAPACITY MEASUREMENT PROCEDURE

Definition: The reference capacity is the capacity of the battery between the 28.2 and 18.0 voltage levels.

1. Charge new or reconditioned battery at the 0.5 C rate for 3 hours.
2. Discharge the battery through a 1.34 ohm load to terminal voltage of 18.0 volts.
3. Charge the battery to 28.2 at the 0.5 C rate; then switch to a 1.0 amp rate and charge to 29.0 volts.
4. Discharge battery to 18.0 volts through the 1.34 ohm load. The discharge time (T) times 16.8 amps (average discharge current) equals the reference capacity in ampere-hours (AH).
5. Repeat step 3 and place the battery in the cycle test setup.

NOTE: The average discharge time for the four batteries used in the test program was approximately 34 minutes. The average reference capacity computed in accordance with step 4 was 9.52 AH.